

SOLAR WORLD CONGRESS VIRTUAL CONFERENCE 25-29 OCTOBER 2021

Proceedings

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ISBN 978-3-9820408-7-5

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SWC 2021 Proceedings Editorial

By Conference Chair Dr. Dave Renné

As Chair of the virtual ISES Solar World Congress 2021, it gives me great pleasure to present to you these Proceedings of the Congress technical presentations.

Due to the travel restrictions posed by COVID-19, the Congress shifted to a fully online event, held on 25-29 October 2021. Nevertheless, thanks to the efforts of all of the organizers, and especially the Scientific Committee, chaired by Prof. Eicke Weber, and his co-Chairs, Prof. Elimar Frank and Dr. Caroline Hachem-Vermette; the key partnership of the International Energy Agency Solar Heating and Cooling Programme, the talents of Ms. Arabella Liehr and Ms. Jennifer McIntosh at ISES HQ, and the Congress Organizer, Conexio-PSE, the Congress attracted hundreds of outstanding abstracts covering a broad range of themes and topics, and featured 93 oral and 96 poster presentations. Most of the technical papers that formed the backdrop of those presentations are now available in these Proceedings.

The Congress took place immediately before the 26th United Nation's Climate Conference of the Parties (COP-26), held in Glasgow, Scotland. For nearly 30 years, the UN Framework Convention on Climate Change (UNFCCC) has convened these annual COPs to bring governments from around the world together to find solutions to the growing climate crisis caused by human activity. During this same 30-year period, renewable energy technologies, and especially solar and wind technologies, have grown from laboratory research and niche markets to a major global commercial success story. Since 1970, the renewable energy community has been documenting its research results and success stories at the biennial ISES Solar World Congresses, and demonstrated how these technologies have become increasingly reliable, efficient, and cost effective. Today, solar and wind energy system costs are competitive with most conventional energy sources, and they continue to drop. Global installed solar and wind capacity now exceeds two and a half Terawatts, much of it used for power generation. Their low cost has made them the preferred choice for new power generation in many parts of the world, and of course the primary means by which countries can achieve their climate mitigation goals.

The work presented in the Proceedings continues this long tradition of reporting on renewable energy growth and development and provides a strong message to the climate negotiators: renewable energy technologies are the solution to capping global warming at 1.5 °C above preindustrial levels as agreed to by virtually all nations at COP-21 in Paris back in 2015. Further technology innovations, and improved financing schemes and policies (especially driven by climate mitigation measures) will further accelerate this growth of renewable technologies in the years to come, and we look forward towards reporting on this growth in the Proceedings of future Solar World Congresses.

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Scientific Program Theme Chairs:

Perspectives for a 100% RE World Andrew Blakers, ANU / Sven Teske, University of Technology Sydney

c-Si Photovoltaics Masafumi Yamaguchi, Toyota Technological Institute / Brett Hallam, University of New South Wales

Other PV Technologies Michael Graetzel, EPFL / Charlie Gay, Violet Power

Innovative PV Deployment Thomas Reindl, SERIS Singapore / Ricardo Ruther, Universidade Federal de Santa Catarina

Solar Thermal Electricity and Fuel Production Ashvini Kumar, TERI / Manuel Romero, imdea Grid Integration Angelina Galiteva, Renewables 100 Policy Institute / Rodrigo Moreno, Universidad de Chile

Solar Heating and Cooling Technologies Korbinian Kramer, Fraunhofer ISE / Andreas Häberle, Eastern Switzerland University of Applied Science

Renewable and Efficient Heating and Cooling Systems Ulrike Jordan, University of Kassel / Cristoph Brunner, AEE INTEC

Thermal Energy Storage Luisa Cabeza, University of Lleida / Anasastia Stamatiou, University of Applied Science and Arts Luzern

Solar Resource Assessment and Energy Meteorology Richard Perez, University of Albany / Carmen Koehler, p3r solutions

Solar Building and Urban Design Alexandra Troi, Eurac / Maria Wall, University of Lund

ISREE 14: 14th International Symposium on Renewable Energy Education Paulette Middleton, Panorama Pathways / Larry L. Kazmerski, University of Colorado

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Themes and Topics

Theme 1 | Perspectives for a 100% RE World

- Results of Global or Regional Scenario Studies that reflect needed Capacities, Horizons, and Costs
- Societal Changes/Perspectives/Issues
- Equity, Energy and Social Justice
- Power-to-X

Theme 2 | c-Si Photovoltaics

- C-Si PV Cell Research and Technology
- Material Issues
- Module Technologies
- PV Manufacturing
- Reliability
- Recycling and Sustainable Material Usage
- Heterostructures on Si including Si Tandem

Theme 3 | Other PV Technologies

- Other Crystalline Solar Cells such as III-V, CdTe and CIGS
- Perovskites and Perovskite Silicon Tandems
- Molecular Photovoltaics (dye sensitized and organic PV)
- Quantum Dots as Light Harvesters
- Heterostructures on other s.c.

Theme 4 | Innovative PV Deployment

- Agri Photovoltaics
- Floating Photovoltaics
- Building-Integrated Photovoltaics
- Car-Integrated Photovoltaics
- Infrastructure Photovoltaics
- Wearable and Consumer Product-Integrated Photovoltaics

Theme 5 | Solar Thermal Electricity and Fuel Production

- CSO and CST Systems
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- Solar Receivers and Heat Transfer Media
- Power Cycles and Cogeneration
- Solar Fuels and Chemicals
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- Solar-Driven Carbon Capture and Utilization

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- Integration of Variable Renewable Energy into large Grids
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- Markets & Policy
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- Smart Grids and Microgrids
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- System Flexibility and Security
- Reliability and Resilience of low-carbon Grids

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- Solar Thermal and Hybrid Collectors
- Thermal Energy Storage
- Domestic Solar Water Heating and Combisystems
- Innovative Components and/or Materials
- Technical Characterization: Testing, Standards and Certification
- Durability and Life Cycle Analysis
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- Hybrid Heating and Cooling Systems
- District Heating
- Heat for Industrial and Agricultural Processes
- Solar Refrigeration and Air Conditioning
- Solar Cooking and Food Processing
- Disinfection, Decontamination, Separation of Industrial Process Water and Wastewater
- System Performance Assessment
- Digitalization and Optimization of Hybrid Renewable Energy Supply
- High Temperature Processes

Theme 9 | Thermal Energy Storage

- Medium- and High-temperature Thermal Storage
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- Storage Applications
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Theme 10 | Solar Resource Assessment and Energy Meteorology

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- Solar Resource Management and Applications
- Solar Resource Forecasting

Theme 11 | Solar Buildings and Urban Design

- Passive Solar
- Daylighting
- Building Integrated / Added PV and Solar Thermal Systems
- Zero-Energy or Plus-Energy Buildings/Neighborhoods
- Zero- or Low-Carbon Emission Buildings/Neighborhoods etc.
- Methods and Tools (to analyze the design of solar buildings and/or neighborhoods)
- Solar Planning
- Building Renovation Solar Strategies

Theme 12 | ISREE 14: 14th International Symposium on Renewable Energy Education

- Renewable Energy Transformation Essential Education
- Interpersonal Skills (communication, teamwork, critical thinking)
- JEDI principles (justice, equity, diversity, inclusion)
- Sustainability guidelines (efficiency, wise use, circular economy)



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Scientific Program

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Techno-Economic Analysis of Green Hydrogen Production from Solar Energy in MENA and Transport to Central Europe

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Abstract

This techno-economic study investigates a Power-to-Hydrogen (PtH₂) and Power-to-Methane (PtCH₄) process chain producing 120 TWh (higher heating value, HHV) hydrogen or methane per year. The aim is to estimate the efficiency as well as the production cost of green hydrogen and methane from solar energy in the MENA (Middle East and North Africa) region followed by transport to central Europe. The examined PtH₂ process chain includes a photovoltaic (PV) system, desalination system, Polymer Electrolyte Membrane Electrolysis (PEM), H₂-storage, and pipeline transport. The PtCH₄–process chain contains an additional unit to capture CO₂ from air (direct air capture, DAC) and a methanation unit. Two key aspects are evaluated in this study. The first is the evaluation of optimal capacities of the electrolysis plant with respect to PV capacities and second, the challenge of storing large amounts of hydrogen due to volatile hydrogen production. Results suggest that the cost of hydrogen production in the MENA region and its transport to Central Europe are $12 \notin$ -cent/kWh in 2021 and $6 \notin$ -cent/kWh in 2050, whereas the purchase costs of methane are 19 \notin -cent/kWh and 9 \notin -cent/kWh respectively.

Keywords: Electrolysis, Green hydrogen, MENA, Photovoltaics, Power-to-gas, Process chain, Techno-economic analysis

1. Introduction

The current worldwide consumption of H₂ is 120 Mt or 4,700 TWh (HHV) (2018) (Gielen et al., 2019). According to political initiatives such as the European Green Deal, the hydrogen demand will continue to increase (Europäische Kommission, 2019). 95 % of the hydrogen is currently produced from fossil sources (Gielen et al., 2019), which causes high CO₂-emissions. As anthropogenic greenhouse gases have significantly affected the world's climate, the reduction of CO₂ emissions during the H₂ production process is crucial for H₂ to become a renewable and sustainable energy carrier. Electrolysis using renewable energy and water seems to be a promising technology for the production of carbon neutral green hydrogen. However, large-scale green hydrogen production requires large amount of renewable electricity. Geologically, due to the availability of intense solar radiation, the MENA region holds a high potential to supply energy using photovoltaics (PV) for the production of green hydrogen (Jensterle et al., 2019; van Wijk et al., 2019). In this work, a Power to Hydrogen (PtH₂) process chain in Morocco is assessed that covers the expected German H₂-consumption of 120 TWh (HHV) in 2030 (BMWi, 2020). Additionally, the integration of a CO₂-methanation in the PtH₂ process chain for the production of renewable methane (CH₄) is evaluated. The examined process chain (see Fig. 1) includes solar power generation, water conditioning, electrolysis, and transport to Central Europe. For the alternative Power-to-Methane process chain, this study further investigates a CO₂-capture and a methanation unit.

2. Process chain

To calculate the purchase costs of H_2 in Central Europe, for each part of the process chain (see Fig. 1) the costs are calculated separately using the annuity method (Verein Deutscher Ingenieure, 2012). The sum of levelized costs of hydrogen (LCOH) and transport costs constitute the purchase costs. For the exact location of H_2 -production, many regions in MENA are possible. According to different studies, due to its political stability, specialist workers and infrastructure, Morocco is deemed to be a suitable location (Jensterle et al., 2019; van Wijk and Wouters).



Fig. 1: Process chain of hydrogen production in MENA and pipeline transport to Central Europe. Additional possibility of methanation after H₂-production.

The electrolysis modules make up the main part of the whole process, producing 120 TWh (HHV) H_2 in the desert of Morocco. In contrast to the other systems, PEM electrolysis has many advantages. PEM electrolysis has a flexible response to load changes and hydrogen is produced at increased pressure (see Tab. 2) (Smolinka et al., 2018). These advantages are particularly important with regard to fluctuating electricity generation and the subsequent hydrogen transport using pipelines. Hence, this study considers a PEM electrolysis system for the following calculations. PV cells convert solar radiation into electricity and supply the renewable electricity for electrolysis. Apart from renewable electricity, hydrogen production requires large quantities of freshwater. Freshwater scarcity is a problem especially in MENA. This study considers the desalination of seawater via reverse osmosis as freshwater source. The last part of the process chain forms the hydrogen storage and transport via pipelines (3,000 km). This also includes the compression of hydrogen before its injection into the gas transportation network.

The integration of H_2 in sectors like industry, energy transport, heat and mobility requires changes in existing infrastructure, which is not expected in the short term. Further, H_2 cannot be used in certain sectors at all. To mitigate this, this study investigates a further conversion of hydrogen with carbon dioxide (CO₂) into methane. The conditioning of CO₂ can be performed by capturing it from flue gas of industrial processes like cement production or from ambient air (direct air capture, DAC) (Schäffer et al., 2019). This study primarily investigates capturing CO₂ via DAC. In the DAC process, large quantities of air pass through an adsorbent. The CO₂ adsorbs on the absorbent until it is saturated. The pure CO₂ is then released by heating and applying a vacuum. During the methanation process, carbon dioxide reacts with hydrogen in the presence of a catalyst to produce methane (eq. 1). Suitable rector concepts are fixed bed reactors, bubble columns or honeycomb reactors (Götz et al., 2016).

 $CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O \quad \Delta_R H = -165 \ kJ/mol \quad (eq. 1)$

As a last step, the CH₄ is transported via the existing European natural gas pipeline system to Central Europe.

3. Techno-Economic Analysis

3.1 Simulation of PV power generation

This chapter describes the simulation model applied to evaluate the PV and electrolysis capacities ($P_{PV,max}$, $P_{ELY,max}$) with the goal of minimizing H₂ production costs corresponding to a given solar irradiation profile. The power generated in the PV module fluctuates depending on the weather data. To evaluate $P_{PV,max}$ and $P_{ELY,max}$, the fluctuating PV power P_{PV} (t) is simulated from real weather data at a reference location with the same solar radiation as in MENA (e. g. Morocco) for one year (Wetter et al., 2014). The weather data consists of horizontal diffusive and global solar radiation with a temporal resolution of 15 minutes. The simulation model calculates solar irradiation H_S (t) from weather data on tilted module according to the PV performance indicators orientation, inclination of modules and latitude (see Tab. 1).

Tab. 1: PV performance indicators

Orientation	South
Inclination of modules	25 °
Latitude	34 °
Efficiency	$\eta_{\mathrm{PV}} = 17$ %
Active area	$\eta_{\text{active area}} = 89 \%$
$H_{ m S,max}$	858 W/m²

With solar irradiation $H_S(t)$, efficiencies of PV (see Tab. 1) and PV area A_{PV} , the simulation model calculates the time-resolved PV power $P_{PV}(t)$ for one year (eq. 2).

$$P_{PV}(t) = H_S(t) A_{PV} \eta_{PV} \eta_{active area}$$
(eq. 2)

 P_{PV} (t) is restricted by the nominal capacity $P_{PV,max}$, which depends according to (eq. 2) on the maximum solar irradiation $H_{S,max}$, PV efficiencies and the PV area. Maximum solar irradiation and PV efficiencies are given parameters, whereas the PV area is variable and has to be adjusted to obtain the required $P_{PV,max}$.

Fig. 2 shows P_{PV} (t) (black line) for a PV area of 852 km² with the corresponding nominal capacity $P_{PV,max} = 110,7$ GW. These two values result from the economic optimization described in the following chapter.



Fig. 2: Fluctuating PV power from weather data (Wetter et al., 2014). Total area $A_{PV} = 852 \text{ km}^2$, $P_{PV,max} = 110.7 \text{ GW}$, $P_{ELY,max} = 66.4 \text{ GW}$

The electrolysis unit undergoes transient operation to be synchronized with fluctuating renewable energy production. The solid green line in Fig. 2 shows the time dependent power input required by the electrolysis $P_{\text{ELY}}(t)$, which equals the generated power of PV. The time during the day in which solar radiation is at maximum and the PV plant output is highest does not last long. To still achieve high full load hours of electrolysis, it is essential to optimize $P_{\text{ELY},\text{max}}$ with respect to $P_{\text{PV},\text{max}}$. The optimal ratio of these two parameters is evaluated by a parameter sweep described in the following chapter. The parameter optimization results in a value for the nominal capacity of $P_{\text{PV},\text{max}} = 66.4$ GW (see dashed green line in Fig. 2).

3.2 Parameter sweep

This study investigates a techno-economic analysis of a PtH₂-chain producing an annual amount of $E_{\text{H2,ELY}} = 120 \text{ TWh H}_2$ (HHV). According to (eq. 3), assuming an efficiency (η_{ELY}) of 73 % for the electrolysis plant (Tab. 2), the annual production of 120 TWh requires $E_{\text{el,ELY}} = 164.4 \text{ TWh}$ of electrical energy per year.

$$E_{el,ELY} = \frac{E_{H2,ELY}}{\eta_{ELY}}$$
(eq. 3)

Tab. 2: Technical parameters of PEM electrolysis (Smolinka et al., 2018)

Efficiency	$\eta_{\rm ELY} = 73$ %
Spec. energy demand	4.875 kWh (el.)/m ³ (H ₂)
Temperature	< 100 °C
Pressure	30 bar
Size of module	100 MW
Stack lifetime	44,500 h

The nominal capacity of electrolysis $P_{\text{ELY,max}}$ is calculated from the annual electrical energy demand $E_{\text{el,ELY}}$ and the full load hours of the electrolysis plant FLH_{ELY} (eq. 4).

$$P_{ELY,max} = \frac{E_{el,ELY}}{FLH_{ELY}}$$
(eq. 4)

The FLH_{ELY} is variable and depends on the nominal capacities of the PV and electrolysis plants. Higher FLH_{ELY} can be used to lower $P_{ELY,max}$. And this results in lower investment costs for electrolysis. However, high FLH_{ELY} also requires a higher availability of electricity from the PV plant. This implies higher nominal capacities of PV units, which in turn increases PV investment costs.

The focus of this study is to minimize the levelized cost of Hydrogen (LCOH). For this, a parameter sweep is performed with the aim of finding the optimal ratio of nominal capacities for electrolysis and PV ($P_{ELY,max}/P_{PV,max}$) that would minimize the LCOH (see Fig. 3). The parameter sweep is performed by variation of $P_{ELY,max}$ for a constant $P_{PV,max} = 110.7$ GW. Finding the value of constant $P_{PV,max}$ is an iterative process. The iteration is finished when at the ratio with lowest LCOH the electrolysis plant delivers the required amount of hydrogen ($E_{H2,ELY} = 120$ TWh (HHV)). One iterative step includes the following calculations for each ratio between $P_{ELY,max}/P_{PV,max} = 0.1 - 1$ in steps of 0.1:

• The FLH_{ELY} are calculated by integrating the dynamic electrolysis power input P_{ELY} (t) (see Fig. 2) over one year, divided by $P_{ELY,max}$ (eq. 5 or (eq. 4 transposed).

$$FLH_{ELY} = \frac{\int_0^t P_{ELY}(t) dt}{P_{ELY,max}}$$
(eq. 5)

• The utilization is defined by the ratio of annual electricity demand of the electrolysis $E_{el,ELY}$ unit to the maximum possible electricity generation $E_{el,PV}$ (eq. 6).

$$Utilization = \frac{E_{el,ELY}}{E_{el,PV}} = \frac{\int_0^t P_{ELY}(t)dt}{\int_0^t P_{PV}(t)dt}$$
(eq. 6)

• Specific investment of electrolysis CAPEX_{spec,ELY} is defined by the annual investment of electrolysis CAPEX_{a,ELY} divided by the energy amount of annual produced hydrogen (eq. 7). CAPEX_{a,ELY} is calculated by annuity method, where CAPEX_{i,ELY} is the initial investment at given nominal capacity, i = 0.691 is interest rate and n = 20 a is depreciation time of electrolysis plant.

$$CAPEX_{spec,ELY} = \frac{CAPEX_{a,ELY}}{E_{H2,ELY}} = \frac{\frac{CAPEX_{i,ELY}}{\sum_{t=0}^{n} \frac{1}{(1+i)^{t}}}}{E_{H2,ELY}}$$
(eq. 7)

• Levelized cost of electricity (LCOE) results from the sum of annual investment and operational costs divided by the energy amount of electricity used (not produced) for hydrogen production (eq. 8). CAPEX_{a,PV} is, calculated by annuity method (eq. 7) from the initial investment costs for at given nominal capacity with an is interest rate of i = 0.691 and depreciation time n = 25 a is for electrolysis plant.

$$LCOE = \frac{CAPEX_{a,PV} + OPEX_{a,PV}}{E_{el,ELY}}$$
(eq. 8)

• LCOH is defined as the sum of annual investment and operational costs of electrolysis, divided by the energy amount of annual produced hydrogen (eq. 9). The LCOE are included in the OPEX of electrolysis.

$$LCOH = \frac{CAPEX_{a,ELY} + OPEX_{a,ELY}}{E_{H2,ELY}}$$
(eq. 9)

The calculation of the parameters described above is based on specific cost data from literature (see Tab. 3).

Tab. 3: Economic parameters for PV and PEM electrolysis plant

	Unit	Today	2030	2050
Interest rate (Bundesnetzagentur, 2017)	%		6.91	
PV				
CAPEX _{PV(Kreidelmeyer et al., 2020)}	€/kW (peak)	550		
OPEX _{PV (Kreidelmeyer et al., 2020)}	€/kW (peak)	12		
LCOE 2030, 2050 (Brändle et al., 2020; Kost et al.,	€-cent/kWh		2.4	1.4
2018)				
Depreciation time	а		25	
PEM electrolysis				
CAPEX _{PV} (Smolinka et al., 2018)	€/kW (el.	619	417	413
OPEX _{PV} (Smolinka et al., 2018)	€/kW (el.	13	8	7
Depreciation time	a	20		

At a low ratio of nominal capacities, high full load hours is possible for the electrolysis unit (Fig. 3, grey bars). At the same time, LCOE is high because of the high amount of unused electricity (green triangles). At $P_{\text{ELY,max}}/P_{\text{PV,max}} = 1$, the full load hours of electrolysis (*FLH*_{ELY}) is equal to the FLH of PV (1,700 h/a). In this case the LCOE is low but due to higher electrolysis investment costs, the specific CAPEX_{spec,ELY} rise (black crosses). The utilization of the solar energy rises with the ratio of nominal capacities and at $P_{\text{ELY,max}}/P_{\text{PV,max}} = 1$ the utilization is 100 %.



Fig. 3: Parameter sweep to find the minimum levelized costs of hydrogen. Depreciation time PV or ELY: 25 a or 20 a, interest rate (both): 6,91 %, CAPEX_{PV} = 550 ϵ /kW (peak), OPEX_{PV} = 12 ϵ /kW (peak)/a, CAPEX_{ELY} = 619 ϵ /kW (el), OPEX_{ELY,fix} = 13 ϵ /kW (el)/a

The parameters described above, influence the LCOH (red dots) and cause a minimum at a ratio of $P_{\text{ELY,max}}/P_{\text{PV,max}} = 0.6$. Tab. 4 shows the set of parameters that results from the minimum ratio.

LCOH	10 €-cent/kWh		
LCOE	3.9 €-cent/kWh		
FLH	2,450 h/a		
Utilization	87 %		
Ratio P _{ELY} /P _{PV}	0.6		
P _{ELY,max}	66.4 GW		
P _{PV,max}	110.7 GW		

1 ab. 4: Kesuns from parameter swee	Tab.	4:	Results	from	parameter	sweet
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3.3 Transport and storage

Various options are possible for transporting hydrogen from Morocco to Germany. It is possible to transport hydrogen via a newly built hydrogen pipeline or via a repurposed natural gas pipeline. Another possibility is to liquefy the hydrogen and transport it by ship. Furthermore, the hydrogen can be transported chemically bound in form of liquid organic hydrogen carrier (LOHC) or ammonia. As suggested in several studies, this study examines the construction of a new H₂ transport pipeline from Morocco via Spain and France to Germany (see Fig. 1) (Gielen et al., 2019; Michalski et al., 2019; van Wijk et al., 2019; van Wijk and Chatzimarkakis, 2020).



Fig. 4: Pipeline transport route from Morocco via Spain and France to Germany (3000 km)

Hydrogen injection into the gas pipeline is not continuous due to volatile production. Huge hydrogen buffer tanks

or underground storages are therefore needed to homogenize the gas flow into the pipeline. As buffer tanks need lot of space and underground storage in Morocco is not sufficiently studied yet, this work suggests a conceptual design in which the first part (400 km) of the gas pipeline is used as the storage unit. The first part has the required capacity to store 52 Mio. m^3 (NTP) and balances the fluctuating H₂ production, while the second part (2,600 km) transports the hydrogen to Europe. The first part of the transport pipeline risks large pressure fluctuations and hydrogen embrittlement. This means that the pipeline material and design may be subject to high safety requirements which may lead to higher costs.

The maximum pressure in the H₂ pipeline is 100 bar with a pressure loss of $\Delta p = 0.175$ bar/km at maximum gas velocity of $v_{gas} = 20$ m/s. The distance of compressor stations is restricted by the maximum pressure loss of $\Delta p = 50$ bar, which leads to a compressor distance of 250 km in the second part of the pipeline. The compressors are driven by renewable electrical energy, as using valuable hydrogen for the turbine would increase the OPEX. The CAPEX of H₂ transport consists of investment costs for the pipelines (material, labor, right of way) and compressors. OPEX include costs for electricity and maintenance. All technical and economic parameters for the H₂ transport are shown in Tab. 5 and Tab. 6.

		Unit	Part 1	Part 2
sor	Compressor capacity P_{Comp}	MW	673	-
d press	Pressure in p_{in}	bar	30	-
Hea	Pressure out p_{\max}	bar	100	-
	Transport capacity	GW (CH ₄ HHV)	48	26
Pipeline and compressor stations	Utilization	h/a	2,475	4,500
	Max.pressure p_{ein}	bar	100	100
	Min. pressure p_{\min}	bar	20	56
	Length L	km	400	2,600
	Diameter d	inch	56	48
	Velocity v _{gas}	m/s	28	20
	Compressor power P_{Comp}	MW	246	164
	Polytropic efficiency η_{poly}	%	90	90
	Electric efficiency $\eta_{\rm el}$	%	90	90
	Effficiency, shaft η_{Welle}	%	98	98
	Compressor distance	km	133	250
	Number of compressors	-	2	11

Tab. 5: Technical parameters of pipeline transport

		Unit	Part 1			Part 2
	LCOE Morocco (Brändle et al., 2020; Kost et al., 2018)	€-cent/kWh	2020	2030	2050	-
			3.9	2.4	1.4	
	LCOE Spain and France today, 2030 and 2050	€-cent/kWh	-			8
	Interest rate (Bundesnetzagentur, 2017)	%	6.91			6.91
Head compressor	Spec. CAPEX (Posch, 2019)	Mio. €/MW	3.57			-
	OPEX (fix)	% of investment	1			-
	ODEX (variable algotrigity)	Mio. €/a	2020	2030	2050	-
	OFEX (variable, electricity)		74	45	26	
	Depreciation time	a	25			-
Pipeline	Spec. CAPEX pipeline (Posch, 2019)	€/m	4,345			3,410
	Spec. CAPEX compr. (Posch, 2019)	Mio. €/MW	3.57			3.57
	OPEX (fix)	% of investment	1			1
	OPEX (variable, electricity)	Mio. €/a	2020	2030	2050	725
			54	33	19	
	Depreciation time compressor	a	25			25
	Depreciation time pipeline	a	50			50

Tab. 6: Economic parameters of pipeline transport

4. Results

Fig. 5 shows the purchase costs of hydrogen produced in Morocco and transported to Central Europe. Purchase costs consist of LCOH and transport costs. Additionally purchase costs of a forecast for the years 2030 and 2050 are presented. Results suggest that purchase costs of H_2 are 12.3, 8.2 or 6.3 \in -cent/kWh H_2 (HHV) for today, 2030 and 2050 respectively. Electricity costs (PV) account with 27 % - 43 % which is the largest or second largest share of costs.





A forecast for 2050 reveals that the costs decrease by nearly 50 % to $6.3 \notin$ -cent/kWh H₂ due to savings in investment costs of electrolysis and PV modules (see Tab. 3). Conventional grey hydrogen via steam reforming costs around $3 \notin$ -cent/kWh (Bär et al., 2021). Compared to conventional H₂ production via steam reforming, H₂ from water electrolysis provides a technology with low CO₂-emissions. CO₂-emissions of steam reforming

process are between 0.25 kg CO₂/kWh H₂ and 0.34 kg CO₂/kg H₂ and emissions from the PtH₂ process are around 0.09 kg CO₂-eq/kg H₂ (Bär et al., 2021). Another possibility to import renewable gas includes the methanation of H₂ with CO₂. Results of the techno-economic analysis of a PtCH₄ process chain (see) investigated other studies is depicted in Fig. 1 (Lehnert et al., 2021). The main aspect here is the economic optimization between H₂-storage volume and methanation capacity to identify minimum CH₄ purchase costs. Results show, that methane purchase costs are higher than hydrogen import costs due to the additional process steps (see Fig. 6). Especially direct air capture accounts for a large part of the costs (19 %) of which 61 % accounts for electricity and heat costs. Lux et al. calculated a similar process chain and has confirmed the results of this study. (Lux et al., 2021)



Fig. 6: Comparison of green H2 and green CH4 purchase costs

5. Summary and Outlook

This study suggests a technical design and economic evaluation of a PtH₂-chain delivering 120 TWh H₂ (HHV) per year to Central Europe. A simulation of time-resolved PV and electrolysis power was performed based on weather data to evaluate nominal capacities. The economic optimization between PV and electrolysis nominal capacity reveals, that LCOH is lowest at a ratio of $P_{ELY,max}/P_{PV,max} = 0.6$. At this ratio, full load hours of electrolysis is 2,475 h/a, the electricity price amounts to 3.9 ε -cent/kWh and the LCOH is estimated to be 10 ε -cent/kWh. Additionally, a technical design of a pipeline system was performed to store large amounts of H₂-and transport the H₂ to Central Europe. The first part (400 km) of this pipeline system has the capacity to store 52 Mio. m³ (NTP) to balance the fluctuating H₂ production and the second part (2,600 km) transports the hydrogen to Europe. Due to high pressure fluctuations in the storage unit, the risk of hydrogen embrittlement and material failure increases. Further investigation is necessary to ensure a reliable operation of hydrogen storage units.

The sum of LCOH and transport costs are the purchase costs. Results suggest that the purchase costs of hydrogen for today, 2030 and 2050 are 12.3, 8.2 or 6.3 €-cent/kWh H₂ (HHV) respectively.

Methane is still used in various sectors like industry, heat, and mobility. In contrast to H_2 , the use of methane requires no transformation of the respective sectors. In addition, the existing natural gas network is capable to transport large amounts of renewable methane without changes in the system. Therefore, no approval processes are necessary and a quick integration of renewable energy in various sectors in form of gas is possible. Still, CH₄ purchase costs (today: 19 \in -cent/kWh CH₄ (HHV)) are higher than H₂ purchase costs due to additional process steps. To improve the efficiency of the PtCH₄ process, an integration of a high temperature electrolysis or the electricity generation by a combination of solar and wind power should be investigated.

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IMPLICIT STORAGE Optimally Achieving Lowest-Cost 100% Renewable Power generation

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Abstract

Implicit storage – aka overbuilt and operationally curtailed variable renewable energy (RE) resources – is a synergistic complement to [real] energy storage for transforming these resources from intermittent to firm, at the lowest possible cost. Firm power generation is an indispensable requirement of ultra-high RE penetration when demand must be met 24/365 without reliance on a core of conventional baseload and dispatchable generation. Analyzing data from a large US TSO, we show that implicit storage is by far the most effective strategy to achieve this intermittent-to-firm transformation compared to other strategies that can reduce RE's intermittency: RE blending, demand flexibility, and geographic dispersion.

Keywords: 100% renewables, storage, intermittency, firm power generation

1. Resolving Renewables' Intermittency with Real and Implicit Storage

Transforming intermittent wind and solar – the two easily-accessible renewable resources large enough to massively displace conventional fossil-based generation – into firm, effectively dispatchable generation is a prerequisite for these resources to acquire a grid-dominant position. Both resources are intermittent, driven by weather and seasons. At current levels of penetration, they operate at the margin of a core of conventional dispatchable and baseload generation. An ineluctable requirement for their growth beyond the margin is their transformation from intermittent to firm, i.e., their capability to meet demand 24/365 without fail and without reliance on underlying dispatchable generation.

1.1. Energy Storage

Energy storage, under any of its possible embodiments – batteries, pumped hydro, hydrogen/e-fuels, etc. – is generally considered essential for this intermittent-to-firm transformation.

It is convenient to regroup current and future storage grid applications into three categories: (1) regulation/ancillary services; (2) intra-day peak shaving and ramp management; (3) long term storage for firm power generation. The first two are directly or indirectly monetizable within the context of existing markets and regulations, e.g., via targeted remunerations, or price arbitrage. The third application is fundamental to ultra-high RE penetration – the subject of this article – but is not yet directly monetizable.

- <u>Regulation Ancillary services</u>: storage is deployed to correct small demand/supply mismatches, that occur because of e.g., RE supply or demand forecast uncertainties. Storage systems can contribute effectively to frequency control, spinning reserves and operating reserves (e.g., Rebours et al., 2007). The stored energy transfer involved in ancillary services typically amount to an infinitesimal fraction of the total demand i.e., a small market for storage overall. Monetary vehicles exist today to monetize this service (Fitzgerald et al., 2015, Mendelsohn & Weiss, 2021) but market size is limited (at most equal to the volume of the fluctuations) [c].
- <u>Ramp management and peak shaving</u>: storage is deployed to tackle intraday load shape issues that are increasingly enhanced by renewable deployments. Managing the peaks and steep ramps surrounding the solar

"duck curve" is a well-known example of this type of management (Wan et al., 2020, Udin et al., 2017, State of Maryland, 2018). Storage can already be applied economically in many locations with access to appropriate remuneration pathways (e.g., The sizes of storage involved for these applications are considerably larger than for ancillary services (Wang et al., 2019, Torabi et al., 2019, Denholm, et al., 2015). However, while power capacities can amount to a substantial fraction of the load, energy capacities remain a small fraction of the overall load.

• <u>Firm RE power generation</u>: storage is applied to enable intermittent RE to displace underlying conventional dispatchable and baseload resources. This task requires large quantities of long-term storage, to make up for any renewable production "droughts", e.g., for solar at higher latitudes, extended cloudy periods during winter. The quantities of storage involved can amount to many days' worth of renewable production. Applying storage alone has been shown to be prohibitively expensive, even when applying the most optimistic future storage technology cost estimates (Perez et al., 2019).

1.2. Implicit Storage

We recently introduced the term implicit storage (Perez et al., 2020) to designate the overbuilt and operationally curtailed portion of renewable power plants. Curtailment is still largely viewed as something that must be avoided. This is because current remuneration systems foster a maximization of renewable energy production. However, as counterintuitive as it may appear, overbuilding and shedding a substantial portion of renewable energy production is central to achieving least-cost firm power generation.

Indeed, overbuilding – analogous to Installed Reserve Margin or IRM, in grid operator parlance – drastically reduces the quantity of long term-storage required to deliver firm power 24/365. Several recent studies by the authors and others have demonstrated that the extra cost of overbuilding (implying having to "waste" potential power generation) more than makes up for the decreased cost of required long term storage (Perez et al., 2019). This is qualitatively illustrated in Figure 1. The term implicit storage embodies the catalyst attribute of overbuilding: enabling [real] energy storage to perform its function: firmly supplying power when the renewable resource is insufficient, but at a considerably lower cost. As shown in, e.g., the MISO high renewable penetration study, (Perez, M., 2020), the difference in firm power generation LCOE between a no-curtailment storage-only configuration, and implicit storage configuration can approach one order of magnitude.



24/365 Firm Power Generation

Fig. 1: Achieving firm power generation with PV. Left: PV and storage alone; maximized production with no curtailment (also referred as "dump" PV). Right: Overbuilt, curtailable "flexible" PV including optimized real and implicit storage.
The optimum amount of implicit storage is the amount that minimizes the firm levelized cost of energy (LCOE) for meeting demand 24x365. This amount depends (1) on the capital and operational costs of the considered intermittent renewable resources compared to storage, as well as (2) on the availability of these renewable resources vis-a-vis the load to be served.

In practice implicit storage optimization requires time/site-matching data time series for the nominal production of the considered renewable(s) and for load demand. The cost of meeting demand without implicit storage is first determined by calculating – and pricing – the quantity of storage necessary to make up for all renewables deficits with respect to demand. The size of the implicit storage is then gradually increased, and the storage determination process is repeated stepwise until the firm production cost reaches a minimum. Increasing implicit storage (i.e., overbuilding the renewable resources and producing more energy than required) implies that a fraction of the output will not be needed to meet demand either directly or via storage, hence will be operationally curtailed. When more than one renewable resource are involved, this process will also involve a least-cost optimization of the their respective contributions.

We illustrate the implicit storage determination in the simple case of PV-only in Figure 2. The Y axis represents the LCOE for meeting demand 24x365. The X axis represents the amount of PV output that is operationally curtailed. Implicit storage and proactive operational curtailment are linked by the following relationship:

$$IS = 1 - \frac{1}{((1 - 0C))}$$

where *IS* represents the implicit storage expressed as a fraction of installed PV, and where *OC* represents the fraction of proactively curtailed (i.e., non-monetized) PV output

The stepwise process of increasing implicit storage defines a U shape curve. The least-cost firm power is achieved at the minimum of the curve, thus defining the size of implicit storage relative to the uncurtailed fraction of PV.

This illustrative example is for the central US region referred in section 2 assuming a homogenous geographic dispersion of the PV resource, and assuming a (future) turnkey PV cost of \$400/kW and a storage cost of respectively \$50/kWh for energy capacity and \$150/kW for power capacity. Experimental data time series applied to this example consist of hourly load data and time/site-specific PV simulated from high-resolution SolarAnywhere irradiances and meteorological data (SolarAnywhere, 2021). The experimental data cover the year 2016. Note that all LCOE calculation assume a 4% cost of capital representative of the US utility industry at the time of this writing.



Fig. 2: Firm Power LCOE as a function of proactive operational curtailment (OC) in the case of a PV-only configuration. The cost contributions of PV, implicit storage and actual storage add up to the LCOE.

2. Implicit Storage vs. other enablers of firm power generation

While implicit storage is an impactful system design configuration to decrease the cost of firm renewable power generation, it is not the only one. Other configuration/strategies that can be combined with implicit storage include:

- <u>RE blend optimization</u>: wind and solar often have complementary availability profiles both a on a daily and seasonal basis. These complementarities reduce the required quantity of real and implicit storage, hence the cost of firm power.
- <u>Flexibility</u>: reduces the firm power requirements by allowing a small fraction of the load to be met by conventional dispatchable resources (supply-side flexibility) or load reduction (demand-side flexibility).
- <u>Geographic dispersion</u>: the geographic smoothing effect reduces the variability of both wind and solar resources, hence also reduces the size of real/implicit storage required to supply firm 24/365 power.

Figure 3 compares the impacts of implicit storage, wind/solar blending, flexibility, and geographic dispersion for a selected electrical region in the Midcontinent Independent System Operator (MISO) interconnected area, starting with a 100% solar/no-curtailment/storage-only configuration, and successively applying implicit storage, wind/solar optimum blending, 5% of supply-side flexibility from dispatchable natural gas, and continent-wide RE geographic dispersion through the entire MISO territory. As for solar above, the wind power generation data are time/site-specific and extrapolated from the majority of wind farms operational throughout the MISO region (Perez, 2020).

Starting at left of Figure 3, we first consider MISO region # 4 with a homogeneously dispersed PV resource at 400/kW. We calculate the LCOE of unconstrained (no-curtailment) PV output with battery storage (50/kWh) as the only resource to deliver 24x365 firm power. This LCOE corresponds to the the leftmost point in Figure 2's curve with an LCOE of ~ 28 ¢/kWh. We then optimize PV oversizing/curtailment and battery storage using the stepwise approach mentioned above to arrive at the minimum LCOE cost of 6 ¢/kWh for region #4. Enter wind power generation at \$800/kW; nominal wind power hourly production data, extraploated from time/site specific wind farms operating in region #4 (Perez, 2020), are added to hourly nominal solar production data to perform a two dimentional stepwise optimization – wind/solar blend and curtailment/storage. This leads to the third column in figure 3 at 4.2 ¢/kWh. When gas is dispatched in this model, it occurs deterministically when aggregate storage resources are entirely empty; this allows gas assets to do some of the energy work which otherwise would be placed on the storage; thereby reducing its necessary size. We assume fully depreciated legacy natural gas resources with an operational cost of 2.8 ¢/kWh. This leads to a resource blend firm power LCOE of 3.5 ¢/kWh. Finally we repeat the combined four steps for the entire MISO region that covers nearly 20% of the USA from the Gulf of Mexico to Canada. Despite assuming no additional transmission costs, the large regional resource spread only produces a modest gain in bottom line LCOE at 3 ¢/kWh,



Fig. 3: Contrasting the cumulative influences of implicit storage (overbuild/curtail), wind/solar blending, load flexibility and TSOwide geographic dispersion on firm power generation Levelized Cost of Energy (LCOE).

3. Least-Cost Enabling Regulations Needed

The above example shows that, for the considered mid-latitude region, the implementation of implicit storage is the most effective system design configuration required to achieving regional firm power generation at an acceptably low cost. (Importantly, the relative cost reductions from one configuration to the next do not depend appreciably on their implementation order.) The effectiveness of this strategy will vary based on latitude and the associated seasonality of the solar resource as one distances from the equator but it is valuable in reducing costs no matter the location.

Unfortunately, current regulation and the remuneration systems they enable do not currently target renewable firm power generation objectives, hence do not enable the most effective solutions that could reach these objectives effectively. Renewable deployment strategies are entirely driven by the way in which existing regulatory policy frames the market: market structure incentivizes actors to deploy capital in specific ways which may not be optimal from a long-term economically sound perspective. Appropriate RPS-like structures specifying optimum deployment of renewable blends and real/implicit storage, or firm-power tariff structures – implying the deployment of implicit storage as a least-cost design solution – are two regulatory strategies that could effectively foster this objective. It is important to stress that the later such strategies will be implemented, the higher the cost of ultra-high RE penetration will be. The longer deployments of unconstrained RE (i.e., w/o implicit storage) continue, the larger the burden – i.e., cost – of future systems will be to achieve firm power generation.

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Where and How Much? Land Use Implications for High-Penetration PV

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Abstract

It is widely known that the solar resource is many times larger than world's primary energy demand. Despite this, questions of where and how much to deploy in a realistic context do not have such clear-cut answers. This article addresses this question in a context where solar PV is applied locally to firmly meet the bulk of energy demand from regional economies across the continental US. We provide comprehensive, realistic and actionable numbers regarding land use and installed capacities to meet present and future load that can inform planning decisions at local and regional levels. We contextualize PV deployment and corresponding land use by assigning a fraction of plausible deployment potential to land use classes as defined by the US Geological Survey. In addition, we provide readers with an online-interactive capability to select land-use deployment availability by class and further investigate state-specific potentials.

1. Introduction

Could photovoltaics power everything? Where could this resource be deployed? How much would such an investment cost? These are central questions as world economies face urgent and far-reaching decarbonization decisions.

In this article, we examine the case of photovoltaics (PV) supplying the majority of primary energy needs for the continental US (CONUS), including the electrification of the ground transportation and building sectors.

We first evaluate state-specific demand-side energy requirements before identifying PV deployment options to meet these requirements. We assume that meeting this demand is most-economically achieved through overbuilding renewable assets by 50% past what is needed on an energy basis: a strategy known as implicit storage (Perez, 2020). This degree of overbuilding has been identified as the cost-optimal amount needed to overcome intrinsic resource intermittency when firmly meeting 95% of demand in locations as diverse as the central United States, Italy and Réunion island. (Pierro, 2020; Tapaches, 2020)

2. Firm Power – Resolving Intermittency with Overbuilding and Storage

The solar resource is more than large enough to meet the world's energy demand many times over (Perez, 2015). This is true even if one considers the electrification of major energy sectors such as transportation and buildings. Intrinsic resource intermittency across multiple timescales, driven by stochastic meteorological processes, as well as deterministic daily and seasonal cycles poses the primary barrier to achieving high-penetration. If solar photovoltaic (PV) generation is to become grid-dominant and supply electrified world economies, this intermittency barrier must be crossed.

<u>Intra-day vs. multi-day intermittency</u>: Issues like ramp rate reduction and peak supply/demand flattening (Chen, 2020; Martins, 2019) can be considered intra-day issues. Energy storage is often employed as a costeffective solution to address the intra-day intermittency driving these issues (Fan, 2020; Telaretti, 2020). From an energy balance perspective, multi-day and seasonal intermittencies drive a much more significant and costly issue to solve. Of interest is retaining stability during prolonged cloudy periods during low-yield seasons. Relying on storage alone to resolve these multi-day issues and ensure firm power production 24/365 would be overwhelmingly expensive– see Fig 1.

<u>Overbuild/curtail *implicit storage* solution</u>: We showed in a recent series of articles (Perez, 2020; Pierro, 2020; Tapaches, 2020) that overcoming PV intermittency and firmly meeting utility demand 24 hours per day and 365 days per year was economically possible well before 2050 in many global regions. Firm PV electricity production costs (LCOE) of the order of 5¢/kWh or less were found to be achievable on a straight financial

basis¹ without major technological breakthroughs. However, we also showed that these low production costs were contingent on one fundamental strategy: <u>*PV resource overbuilding and proactive output curtailment*</u>. This counter-intuitive strategy also referred to as the *implicit storage* strategy, is key to sufficiently reducing otherwise insurmountably-costly long-term energy storage requirements. Other authors have recently employed optimized overbuilding of variable renewable capacities and curtailment in their renewable optimizations for purposes of designing a cost-optimal high-renewables-penetration system but they are each subject to scenario-based constraints more stringent than the CPT model which allows for any capacity of wind, PV and storage to be built to eventually meet load.

Fig. 1 illustrates the impact of oversizing on storage requirements. The [relatively small] amount of storage required to supply power and alleviate intraday imbalances does not change appreciably with oversizing (top part of the figure). By contrast, the multi-day (annual) storage requirements are reduced by over an order of magnitude (bottom part of the figure).



Fig. 1: Contrasting intraday intermittency (top) and multiday intermittency (bottom) and illustrating the impact of oversizing where PV is sized to meet load requirements on an energy basis (left) and PV is 2X oversized (right).

- The top left graph contrasts typical PV production to load requirements intraday. PV is sized to meet load requirements on an energy basis. When applying storage (solid black line) PV energy can be stored and released appropriately to meet intraday (here night time) demand.
- The bottom left graph contrasts [30 day-smoothed] annual PV production and load demand. As above PV is sized to meet annual load on an annual basis. Applying storage can enable PV to meet load at all time. However, the quantity of storage required is nearly 50 times larger than the amount required to resolve intraday supply-demand mismatch.
- At right top, oversizing PV does not sensibly modify intraday storage requirements
- However, the bottom right draft shows that oversizing can meet demand with drastically reduced long-term storage requirements compared to equal energy-sized PV.

¹ 'Straight business' production costs before tax, without including any environmental benefits or any other incentives.

Fig. 2 from (Perez, 2019) illustrates the economic impact of overbuilding PV. It shows how this is central to achieving acceptable least-cost firm power generation. Across the case studies analyzed, oversizing factors of the order of 50% were found to be conservatively optimal¹ given future expected costs for PV and energy storage (Pierro, 2020; Tapaches, 2020), even considering the most optimistic 'ultra-low-cost' storage cost projections (Dhieber, 2020).

Further, we showed that optimally combining solar and wind resources, and allowing for some supply-side flexibility with a residual natural gas² fraction (<5%) could drive projected firm power generation costs well below current conventional generation costs.



Fig. 2: While unconstrained, intermittent renewable generation costs will achieve very low targets (A) – they are already below grid parity (D) – transforming PV into the firm, effectively dispatchable resource needed by the world economies will be very costly if done with storage alone (B), even when considering the most aggressive future cost projections for storage. Overbuilding renewables can reduce the storage requirements, to the point where "true" below parity firm generation will be attainable (C) – source (Perez, 2019).

These low prospective firm power generation costs let us envision an economically sound transition from business-as-usual fossil-based energy sources, to renewable sources -- even before accounting for external environmental benefits. Importantly, we also argued that, once firmed-up - i.e., rendered effectively dispatchable – intermittent renewable resources become operationally equivalent to conventional dispatchable, baseload, or peaking generation. Overbuilding allows renewables facilities to ramp up and curtailment allows these facilities to ramp down at multiple timescales, as needed by supply and demand conditions. Optimally minimized storage manages the remaining imbalance. Ultra-high penetration deployments could therefore occur without fundamental power grid restructuring.

Finally, we underscored that evolving from the current [intermittent] marginal PV generation paradigm – relying on a core of conventional baseload and dispatchable generation -- to a [firm] grid-dominant paradigm would depend less on technological innovations than on innovative thinking surrounding regulatory/market-structure. In particular, we noted that in order to achieve these aims, remuneration systems would have to

¹ Higher wind proportion and overbuilding will be assumed for electrified heating loads (see below).

 $^{^{2}}$ Here natural gas is a stand-in for flexible, dispatchable generation capable of ramping up and down in short order; cleaner alternative like power-to-gas via H₂ electrolysis and hydroelectric power all have the potential to fill this role.

evolve from a marginal mindset, i.e. rewarding production maximization and treating curtailment as a loss (e.g., today's PPAs as outlined in Mendocino, 2019) to rewarding firm production (i.e., embracing curtailment as the catalyst to least-cost firm power generation).

3. Demand Requirements: How Much PV Generation?

We assume 25% for PV conversion efficiency—reflective of commercial-grade crystalline modules and used in the literature (Cousins, 2010). For array geometry, we nominally consider fixed arrays tilted southward at 10° for increased packing factor. This leads to a peak power density of 200 W per square meter of ground area under standard test conditions. PV fleets are sized according to these assumptions to meet the identified present and future energy demands in each state subject to 50% capacity overbuilding. For each identified fleet, hourly PV production is simulated from high-resolution hourly-interval SolarAnywhere® irradiance and meteorological data spanning 22 years (1998-2019).

The present and future demands fall under three scenarios: (1) Supplying the existing electric sector only (2) Supplying the existing electric and transportation sectors – assuming a complete transformation of the latter to electric, with the exception of air and maritime transport. (3) Supplying the existing electric, electrified transportation, and building sectors (residential/commercial) – with the assumption that the current non-electric building sector HVAC loads (i.e., chiefly heating) would be electrified (Waite, 2020).

2.1 Electric Sector

We first tabulate the existing electrical consumption for each state in the CONUS. This ranges from 6 TWh/yr in Vermont, to 425 TWh/yr in Texas. For each state, we also calculate the capacity factor (kWh_{AC} / kW_{DC}) for PV fleets based on resource availability and the other assumptions outlined above. These capacity factors range from 15.8% in Washington State to 23.6% in Arizona. We then infer the power capacity of PV fleets (including overbuilding) necessary to meet 55% of the loads in each state. Capacities range from 3 GW in Vermont to 193 GW in Texas wile the required PV capacity to serve 55% of the CONUS would amount to 1,958 GW.

2.2 Transportation Sector

The US transportation sector consumes 28% of the country's total primary energy. In 2019, this fraction amounted to 8,400 TWh. The terrestrial transport sectors that we assume could reasonably be electrified amount to 82% of this total, or 6,900 TWh (Waite, 2020). Electrifying transport will yield significant efficiency increases. We assume internal combustion engine (ICE) fleets average 25% efficiency will be replaced with electric fleets averaging 80% efficiency (Helms, 2010). The electrified transport demand would amount to 1,980 TWh annually. Allocating this CONUS wide value by state is performed by using miles driven per capita and population. The PV capacity required to meet 55% of the electrified transportation demand ranges from 2 GW in DC to 103 GW in California and totals 1,088 GW across the CONUS.

2.3 Residential & Commercial Building Sector

The CONUS currently uses 3,173 TWh/year of primary heat energy across the residential (1,862 TWh) and commercial (1,311 TWh) building sectors. Electrification will save 2/3 of this energy given the efficiency of heat-pumps (Tian, 2005)These new electric requirements would thus, respectively amount to 633 and 446 TWh/year for the residential and commercial sectors. We allocate the current total US primary heat energy consumption for each state as a function of (1) their mean heating degree-days (HDDs), and (2) their population. Mean state-specific HDDs range from 292 °C in Florida to 4,994 °C in North Dakota. Importantly for heating, we assume that PV capacity is both more overbuilt (200%) and supplies only 28% of the new heating load given seasonal anticorrelation – the balance is met by wind. The PV capacity required to firmly meet the demand ranges from 1.7 GW in DC to 70 GW in New York and totals 572 GW across the CONUS.

4. Where to Deploy

For the most demanding three-sector deployment scenario (electric + transport + buildings), spatial requirements range from 45 km² in Vermont to 1,566 km² in Texas. To put these numbers in perspective, we also calculate what percentage this surface area represents relative to the size of each individual state. State percentages range from 0.02% in Montana – a large state with low population – to 26% in Washington DC –

a small, almost completely urbanized region. For the entire CONUS, the Electric + transportation + buildings scenario would require 0.25% of total area.

Our approach to contextualize PV deployment considers current USGS ground occupancy categories in each state and assigns reasonable fractions of each category available for PV deployment (the *developable fraction*). The ratio between the surface area available and the surface area required to meet 55% of all load with PV we term 'room to grow.'



Fig. 3: PV Deployment 'room-to-grow' beyond this article's assumption to firmly meet 55% of electricity, transportation and building sector demand with PV, given the possible deployment ground cover scenario listed in the Table 8 – Note: any state-specific land-cover scenario can be interactively investigated by linking to Perez (2021).

Land-use categorization was obtained from the LandSat-derived, 30-m resolution US National Landcover Database (USGS, 2020). The largest assumed developable fraction is for urban landcover where we assume that 15-25% of roofs, parking lots and exclusion zones can be covered depending on density. We entirely exclude forests or wetlands and at the low end include as deployable, 0.3% of herbaceous land.

Except for DC, all states have considerable room to grow. For the great majority of states, the room to grow is such that a 100% PV future instead of the assumed 55%/40%/5% PV/wind/gas blend is conceivable. The map in Fig. 3 graphically illustrates this 'room to grow' quantity. Because the developable fraction is somewhat qualitative and subject to debate, we developed a web application allowing users to interactively set specifics for any US state and groundcover class and assess how deployment potential would be affected (Perez, 2021).

5. Conclusions

In this article, we present a view of a grid-dominant PV sector capable of providing firm power and displacing conventional generation—in line with global research at the International Energy Agency. Firming up intermittent renewables at reasonable cost implies substantially overbuilding generation capacity and therefore occupying substantially more space than needed on an energy basis. The central question of this paper – where to deploy – thus becomes even more pressing.

Considering demand from the US electric sector as well as electrified transportation and building sectors, we investigate whether an optimally oversized PV resource could reasonably be deployed to meet demand. We assume the same resource breakdown as other recent studies: 55% PV, 40% wind, and 5% dispatchable generation. We examined a deployment approach which starts from global land use data derived from LandSat and some reasonable assumptions regarding which fractions of land class types can be used for PV deployment.

We provided solid evidence that a PV-dominant future supplying the majority of the energy demand from three large sectors of the economy was highly realistic from a deployment standpoint. Firmly and economically supplying 55% of these three sectors could require as little as 0.23% of the country's surface with state-specific fractions ranging 0.03% in low-density sunny states, to 2.3% in most densely-populated northeastern state.

Using these numbers for each state and assumptions regarding the deployable surface for each land-use category, we identified the "room to grow" beyond the assumed 55% supply-side fraction assumed to be met by PV. Indeed, a 100% PV option could be considered in all states within the CONUS from a land-use perspective with the exception of fully-urbanized DC. We complemented this article with an interactive web

site - where the deployable surface assumptions could be easily modified on a state-specific basis.

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Total Performance Assessment Method for Industrial Process Heat Systems

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Abstract

A combined performance indicator is developed for specific renewable energy technology solutions, such as industrial process heat, with the target of being able to compare different technology scenarios including energy efficiency measures and supply options in a fair and transparent way. The combined indicator is a sum where the individual parts are obtained for each scenario from individual energy simulations, economic cost calculations and calculation of CO_2 emissions. The combined performance can be presented as a cost figure in \notin related to the total heat demand of all processes in the company. This also enables a simple comparison of energy efficiency measures with renewable supply options. Monetarizing energy and environmental performance by giving primary energy consumption external costs and CO_2 emissions and external costs. Finally, the financial results can also be related to a production specific value. This leads to benchmarking and is an easy way to show industrial managers the energy and environmental profile of their products. A fictitious example case is presented also to illustrate the methodology.

Keywords: Solar process heat, performance assessment, decision making, market uptake

1. Introduction

Today's reality is still far from a climate neutral energy supply with 100% renewables. It is well-known that heat plays a decisive role as nearly 50% of the world's final energy demand is needed as heat. While the rapid progress of photovoltaics and wind in the electricity market is supporting the strive for the 1.5 K target in the threatening climate change, in the giant heat sector -50% of the Total final energy demand TFD - solar heat up to now plays a small role.

One of the biggest theoretical global potentials has solar heat for industrial processes (SHIP), but several barriers inhibit progress in the market. About 85 EJ (22%) of the TFD (377 EJ in 2018) is being used for industrial heat, and more than half for temperatures lower than 400°C (Fig. 1).



Fig. 1: Global Total Final Energy Demand (TFD) 416 EJ (377 EJ energy supply plus 38 EJ non-energy purposes)

The complexity in this sector compared to electricity or fuels supplied as final energy is that heat dissipates and mainly must be supplied locally. Although this may favor decentralized solutions on building or district level using solar radiation, alternative solutions e. g. based on the electrical grid are fully conceivable. Other complexities are the required temperature levels of heat, the possibility to replace processes for example in industry using heat by alternative solutions without that requirement, and moreover the reduction of demand by heat recovery and process intensification.



Fig. 2: Risk categories in SHIP projects

Risks in technology selection, industrial production, costs and adaptation to market and policy changes lead to question-marks related to profit (Fig. 2). Perceived risks are barriers to an uptake of a new technology, however also other factors may contribute.

One of the problems that may hinder decision makers in companies when choosing and implementing a solar process heat system is the multitude of approaches to lower energy bills and reduce carbon footprint: energy efficiency measures and a multitude of system solutions from cogeneration via heat pumps to direct electrification of processes.

A fair and integral performance assessment method including energetic, economic and environmental criteria could support a transparent decision process thus helping the implementation of solar process heat systems.

A simple metric to assess the performance of one system against alternatives is not available. Simple approaches as the levelized cost of heat (LCOH) are falling much too short to provide a full assessment. In this article, therefore, the author presents a total performance assessment method that considers energy, financial and environmental performance. The method needs to be applicable for all technological solutions in the sector. It may help to shape rational decisions of investors.

2. Methodology

The scope of the methodology described covers developing an integrated performance assessment method for technological solutions leading possibly to lower fossil energy consumption, lower emission of greenhouse gases (GHG) like CO₂ at reasonable cost. Energy, environment, and economics (EEE) are addressed, but this is only a selection of possible impacts of a technology. Other important factors like impacts on social life, chance equality, creation of jobs, cultural issues, political power, and many more can be included in an evaluation of a technology. However, in this article the scope will be limited, it is not the idea to develop a full political technology impact assessment. We consider only energy, environment, and economics in relation to alternative investments from the perspective of a company, and secondly, only within the operational phase of a system. If the impact of different systems from cradle to grave shall be evaluated, the method lends itself easily to an extension, if the tool for the individual assessment is available.

The objective of the methodology described here is the assessment of a technology solution for a company to cover the process heat demand in an industrial production. Nevertheless, the approach taken can be equally applied to heating of houses, or to electricity supply of consumers or energy for transport solutions. For the methodology described in the following it is important that a specific purpose of the technology is addressed. This provides the reference system. Multiple purpose solutions therefore will be reduced to the contribution for a specific purpose.

The advantage is that the whole chain leading to a specific aim can be investigated and assessed in the full complexity, for example the investment in energy efficiency measures, new energy saving technologies in production, several solar generation technologies and even energy converters like heat-pumps. The disadvantage is that multiple purpose measures like installing a PVT collector which provides hot water for showering and electricity for say charging an electric vehicle cannot yet be covered with this approach.

A further characteristic of a methodology relates to system boundaries. As already described, we focus here on a company site, and will not investigate impacts on district level or even larger entities like regions or states. This would need a thorough discussion of a suitable output of such an entity, which is beyond the limits of this work. Also, in our example the system boundary excludes the detailed processes used in the industry, because we want to avoid the complex topic of process intensification and alternative production technologies. However, we will keep in mind, that the ultimate goal is to integrate even such issues into the overall assessment.

In summary the methodology presented here is an approach which may be extended in future, if more and more integrated views will be needed. The approach taken is a modular one: aspects may be included or not in an appropriate way, but the principles developed here are only exemplary on the basis of

- Primary energy consumption (fossil fuels and electricity) -for energy performance
- CO₂ equivalent emissions during operation for environmental performance
- Levelized costs during the operational lifetime for financial performance

Many individual performance indicators (PI) have been developed and presented for energy, environment and financial feasibility (Kourkoumpas et al. 2018; Ruegg und Short 2007). Energy PI are manifold, and especially for renewables often used metrics are energy payback time, saved energy, solar fraction, saved fuel, efficiency, or utilization factor. Energy management relies on such metrics which have been already been described and classified in the ISO 50006 standard. Environmental PI often not only include the operation of a system but also the full lifetime from cradle to grave. Life cycle analysis LCA is already a fully developed methodology also described in standards: Concerning products, the leading standards for Life Cycle Assessment (LCA) are ISO 14040 and ISO 14044 (ISO 14044; ISO 14040). However, a full LCA is too complex and costly for a comparison of different conceivable investments. To evaluate the measures, the life cycle assessment of all machines and products used to reduce the energy and environmental footprint in a factory would be required. In LCA many inputs are based on averages and not on the actual processes and supply chains. For the moment, therefore, a restricted and limited indicator is used, for example CO₂ equivalent emissions or Global Warming Potential GWP. Financial assessment of renewable energy investments uses indicators like amortization time AT, internal rate of return IRR, net present value NPV, or levelized cost of energy LCOE. The latter is already an example of a combined PI as it relates energy performance to investment and operational costs.

The basic idea here is that we start from **three main individual indicators** in the areas of **energy**, **economy** and **environment**. It is also possible to derive then a **combined indicator** (Henning 2012). Basically, this is done via monetization of the environmental and energy performance using a weighting factor. As well individual indicators as the combined indicator may be compared to the ones of a standard reference system ("the typical solution"). But on the other hand, reference systems have the disadvantage that the "standard" may be very different in various locations and countries. When the standard is already very efficient a renewable and energy efficiency solution may be underestimated. Therefore, it is suggested to use the sum of the individual existing process heat demands within the process heat system as reference, and then further relate that to the number of certain production units (say a hectoliter of beer, or a ton of yoghurt, or a ton of metallic copper with purity 99.99%).

In the first level – referencing to the **sum of existing process heat demands** – it ensures that also energy efficiency measures reducing the fuel and electricity demand of the plant will positively influence the indicator.

In the second level – relating that to the **number of production units** – this indicator leads even further and establishes a comparison between different production methods also. Introducing a new process intensification step in the production also lowers the heat demand per produced unit and lowers the benchmark for energy use in production. Therefore, this step in a natural way leads to **benchmarking**.



Fig. 3: Approach to a combined performance indicator

The approach to define an integrated total performance indicator not only looking at one aspect but all three factors mentioned is to use a combined PI. Ratio indicators like the LCOH have been proposed to include at least two aspects in an analysis. However how to deal with three (or more) aspects? The solution is the weighted combination of individual PI_k in a combined one:

$$CPI = \sum_{k=1}^{N} f_k \cdot PI_k \qquad (eq. 1)$$

The weighting factors f_k can be adapted and improved depending on new research or new emphasis on one specific performance. For the specific case of investment in environmentally friendly solutions to provide the heat for industrial processes in a factory three factors are proposed.

Suggested Performance indicators - referenced to total process heat demand D:

Energy performance

-> Primary energy consumption (fuel, electricity) per process heat demand PECD [MWh/MWh]

Financial performance:

-> Levelized cost per process heat demand LCD [€/MWh]

Environmental performance:

-> CO2 emission per process heat demand CO2D [t/MWh]

 $\label{eq:combined} \begin{array}{l} \mbox{Combined performance} \mbox{ per process heat demand CPD [ℓ/MWh]:} \\ \mbox{-> CPD} = LCD + f_{PE} * PECD + f_{CO2} * CO2D \end{array}$

As the fuel and electricity price is already included in the LCD, we only need to add a cost number for using a lot of primary energy. We use a monetary factor f_{PE} [\notin /MWh] representing external costs for high primary energy consumption, and a second monetary factor f_{CO2} [\notin /t] appraising the cost of CO₂ emissions. Here we might use as a first guess the (momentarily rather low) price of CO₂ certificates.

The use of primary energy in the energy performance indicator is motivated in the necessary fair comparison of different energy sources. For example, replacing heating energy from a gas boiler by electrical heating may reduce the energy consumption, but – depending on the national electricity production – the electricity might be produced by gas, and due to the efficiency losses of the heat engines and the distribution grid this might be less efficient than the direct burning of gas in the plant. Similarly renewable heating should not lead to high consumption of auxiliary electricity for pumps.

3. Procedure for evaluation

A total performance assessment (TPA) may be done for a planned project in a feasibility study, or it may be performed for an existing and installed plant for real operation. In the latter case experimental monitoring may be used for acquiring the energy data of the plant, and real costs are available for investment and operation. On the other hand, it is difficult to compare that to a different case (say without or with improved solar process heat integration and energy efficiency measures). When using simulation and cost estimates one may however include **several scenarios for a comparison of alternatives**, trying to **rank the performance** of those with a combined performance indicator or by weighting individual indicators with a factor and summing up the points in a table.



Fig. 4: Steps in the evaluation procedure for the comparative combined performance indicator

In a comparative assessment of two or more cases, the following steps must be performed (the calculation of individual PI is not required):

STEP 1: Simulate or monitor a solar process heat (SPH) system including energy efficiency measures (EEM) implemented at the plant over a representative year to have the annual contribution of the solar and conventional heating system to cover the **total process heat demand of all processes** in the plant. Also fuel consumption and savings due to the solar thermal system integration should be evaluated

It is not sufficient to estimate the annual output of partial systems (collector-loop, thermal energy storage), the whole plant should be included in the analysis including the conventional heat supply.

The following intermediate energy indicators may be additionally presented for each scenario:

- Total annual heat demand Q_{demand}
- Total annual fuel and electricity consumption Qann, fuel and Qann, el
- Solar and conventional heat fraction to annual heat demand $f_{solar} = 1 f_{conv}$
- Heat demand per produced unit in the plant q_{spec,unit} (e. g. kWh per hectoliter beer)

STEP 2: Estimate the investment cost and the annual operation and maintenance cost for the plant with (and without) solar process heat (SPH) and energy efficiency measures (EEM). Calculate using the results of Step 1 also the economics of the plant with and without SPH and EEM. The difference of determining LCD to calculating the Levelized Cost of Heat LCOH is that the cost of a scenario is related to the total process heat demand, not the heat delivered.

Optionally, the following intermediate financial feasibility indicators may be presented additionally for each scenario, using the cost estimations from above:

- Total cost over project lifetime C_{pd,total}
- Initial capital cost C_{invest}
- Cost for Business-as-usual C_{pd,bau}
- Profit/Savings Incurred C_{pd,sav}
- Project IRR
- Net present value (NPV) of project

- Payback period [years] t_{payback}
- LCOH of SPH energy over duration of project
- LCOH of plant energy over duration of project

STEP 3: Determine for the location and country the savings in primary energy PE and CO_2 . This gives an indicator for environmental performance. Use country-specific primary energy factors for fuel and electricity and CO_2 emission. For the PE-factor monetizing the use of primary energies for example externalized costs could be taken which try to assess the costs for the society (health, traffic, environmental consumption) of the use of a specific primary energy source. Here the supply contracts for the company make a difference, for example depending on the source of electricity (green or conventional) different factors should be used. For the greenhouse gas emissions (CO_2 -factor) the cost of certificates in a trading scheme could be used. The level of emissions depends very much on the primary energy used.

The following intermediate environmental indicators may be presented for each scenario:

- Total annual primary energy consumption PEC_{ann}
- Total annual CO₂ emissions due to operation E_{ann,CO2}

STEP 4: Calculate a combined performance indicator CPD for each scenario and rank the scenarios. Alternatively, weight and rank the individual indicators for each scenario and sum up the points achieved in a ranking table.

STEP 5: Relate the individual performance indicators and the combined one using the benchmark figure of heat demand per produced unit in the company to calculate CPU.

4. Example case study

In the following I want to describe the fictitious example of a **total performance assessment** for a small dairy company located in Madrid Spain (Fig. 5). The total annual heat demand of the milk processing company is 580 MWh. With that 5550 tons of milk will be processed into diverse milk products. In order to show and demonstrate the applicability of the method, two alternative solutions for covering the heat demand of an industrial plant will be described. As a reference system we have an existing process steam system fed by a gas boiler.

The alternative system is a solar thermal collector system raising the feedwater temperature of the gas boiler. For the conventional boiler system, we assume 90% efficiency and a fractional electricity consumption of 1%. The simulation of the solar thermal system uses the assumptions of an IEA Task 49 study (Case 3) described with the boundary conditions in (Helmke et al. 2013). The resulting solar fraction for the 200 m² vacuum tube collector field with a 12 m³ storage is 32.6%.



Fig. 5: Location Madrid for a fictitious dairy industry

Besides the annual energy demand data for fuel and electricity the investment costs for the solar and the non-solar system part need to be specified. The assumed collector field costs were 350 €/m^2 , the thermal storage costs 800 €/m^3 and the remaining balance of plant 1000 € resulting in an investment of 80600 € plus 20% planning and installation indirect costs. The investment costs for the conventional heating system were arbitrarily set at 12000 € plus 20%. This is called the reference case.

The general economical parameters have been set as well and can be seen in Tab. 1.

Parameter	Symbol	Unit	Value
Project period	ТР	[a]	25
Insurance	d	% p.a.	1.0%
discount rate	dr	% p.a.	7.0%
inflation rate	ir	% p.a.	2.0%
energy inflation rate	ie	% p.a.	2.0%
Operation and maintenance	O&M	% p.a.	1.5%
Indirect cost	C_indirect	[%]	20%
resale value	RV	[€]	0
Fuel prize	c_fuel	[€/MWh]	50 €
Electricity price	c_el	[€/MWh]	250€

Tab. 1: Economic boundary conditions

It is possible to individually calculate individual financial indicators for the two cases, investment of a new

conventional boiler system or investment of a solar heating system plus new boiler. Other cases may be also constructed, as investment in a heat pump system, or simultaneous investment in a solar and a conventional heating system. In our case we calculated the comparative version, where the savings of fuel due to the solar thermal system gains are calculated as income over the operation years.

As environmental benefit we calculate a primary energy saving of 226.4 MWh and a reduction of 41 t CO₂/year. As the last step the combined performance is calculated - in this case for reference case and for the solar integration case. If we want to give a financial value to these savings in the combined indicator we should assess the factors f_{PE} and F_{CO2} for Spain (see Tab. 2).

Factor			value
Primary energy	\mathbf{f}_{PE}	[€/MWh]	2.28€
CO ₂ emissions	f_{CO2}	[€/ton]	20.00€

Tab. 2: Assumed monetizing factors for Spain ((Leoncini 2013; Bradbury und Dender 2016)

Performance indicator			Case	Reference
Levelized cost per heat demand	LCD	[€/MWh]	57.83 €	60.05 €
PE consumption per heat demand	PECD	[MWh/MWh]	0.849	1.239
CO ₂ -Emission per heat demand	CO2D	[t/MWh]	0.156	0.227
Combined performance	CPD	[€/MWh]	62.88 €	67.42€

Tab. 3: Combined performance per heat demand

Using the annual production of 5550 tons of milk we find the specific heat demand 105 kWh heat per processed ton of milk. Using that we convert results of Tab. 3 to the final results in Tab. 4.

۲ab. 4	4: (Combined	performance	per	production	unit
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Performance indicator			Case	Reference
Levelized cost per production unit	LCPU	[€/Unit]	6.04€	6.28 €
PE consumption per production unit	PEPU	[kWh/Unit]	88.6	129.4
CO ₂ -Emission per production unit	CO2PU	[kg/Unit]	16.3	23.7
Combined performance	CPPU	[€/Unit]	6.57€	7.05€

In a relatively simple (financial) number the performance of the two different cases may be seen. In this way different cases and alternative concepts could be evaluated.

5. Conclusion

The main idea and purpose of a total performance assessment TPA is to rank different project alternatives (possibly also including the existing status of the plant) in terms of energy, economic and environmental performance. Decision makers in competitive companies dedicated to green products can thus be assisted using the combined performance to improve their products in all three aspects. Although there are extensive methods that consider the entire life of a plant (life-cycle analysis LCA), we recommend using a much simpler approach using the CO_2 emissions due to operation as environmental indicator, which requires no detailed data from production processes of the product, which often contain confidential information.

For the combination of energy, ecology and economy a combined performance indicator has been defined, however for ranking, also the individual indicators may be used, where weighting may be done in an individual way in a ranking matrix, suitable for the project and customer. The advantage of the combined indicator is the simplicity and transparency. There are no arbitrary weighting factors included. The indicator could be further developed as an international standard.

It is suggested that the indicators are either referenced to the total process heat demand (as determined by calculation or by measurement in the whole process heat system) or by relating the performance to production units (e. g. produced cars in a factory or produced hectoliters of beer) in the factory. It may be used also in non-producing companies using service units e. g. in a laundry or in a car-wash utility. The first version allows to compare completely different alternative approaches to improving the performance of a heat distribution system, including energy efficiency measures like heat recovery or heat storage and renewable generation. The second version also allows such a comparison even including process intensification, i. e. also when the heat consumption of a specific process like drying or washing is reduced by exchanging machinery. Even the reduced demand of an in dividual process step is reflected in the metric. Therefore, the latter method lends itself in a natural way to benchmarking, as energy or cost per produced unit (service unit) will be calculated for the different alternatives of the project.

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Transition Pathways Towards a Carbon-Neutral Thuringia

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Abstract

Energy scenarios are used to better understand the effects of political or technological choices in the transformation of energy systems. These are complex calculations that, determine for example a cost- or emission-optimized configuration of an energy system under predefined boundary conditions. From them, both the need for action and the freedom of design can be derived. This paper presents an energy system would based on hourly load, generation and price profiles for the German state of Thuringia. The energy system was modelled in the open source energy modelling framework oemof. Taking into account the local energy potentials, the development of energy demands and prices, the results show how the climate policy goals of the federal state of Thuringia can be achieved and which transformation pathways are possible along the timelines 2030, 2040 and 2050.

*Keywords: energy system, modelling, oemof, climate neutral, transition pathways, CO*₂*-price, energy scenarios, energy policy, Thuringia, sector coupling*

1. Task

As a result of the World Climate Agreement in Paris, in which it was agreed to curb global warming, the Federal Government has set concrete CO_2 reduction targets for Germany. These targets can be broken down to Thuringia, although the Free State has set itself some more far-reaching targets in its Climate Act (ThürKlimaG, 2018): By 2030, Thuringia's greenhouse gas emissions are to be reduced by 70 % compared to 1990, by 2040 by 80 % and by 2050 by 95 %. In addition it is stipulated that 55 % of the total energy demand is to be covered by renewable energies in 2030 and 100 % since 2040. That means that the entire energy demand must be covered by renewable energies on the balance sheet, so that fossil energy sources may only be used if the same surplus of renewable energies is produced at another time. In 2030, moreover, 80 % of electricity demand is to be covered by renewable energy generation.¹

How such a climate-neutral energy system can look like in 2050 for an industrialized region like Thuringia, which technologies are available to cover our energy demand for electricity, heat and mobility and finally, which steps politics and society must take to achieve this, can be answered by energy system models. They can be used to calculate which renewable energies are needed in which amount (i.e. with which output), and which composition of sector coupling technologies and storage systems is needed to optimize the energy system according to minimized economic costs, taking into account the given restrictions. The model results can be used to derive economic expansion pathways (transformation pathways) for technologies.

2. Approach

As a basis, the question arises as to how energy demand will develop in the future. To this end, various factors need to be illuminated, as shown in Tab. 1. The first is demographic change. Both the decline in population and the increase in the average age will lead to a decline in the number of private households and thus in the general energy demand. On the other hand, there is the factor of climate change: due to the higher average temperature, the heating demand will decrease. But this effect is overcompensated by a sharply rising air-conditioning demand and consequently the electricity demand will increase. Energy efficiency guidelines generally ensure lower energy

¹ The targets, set out in the Thuringian Climate Act (ThürKlimaG, 2018), form the basis of the scenarios presented in this paper. The scenarios will continuously be adapted to the actual political discussion in Germany resp. Thuringia – for example carbon neutrality in 2045.

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demand. Building renovation reduces the demand for heat in particular. In the future, this will increasingly be provided by heat pumps, which, however, as Power-to-Heat (PtH) technology, generate a higher electricity demand. Electricity demand is also rising due to the increase in electro-mobility. The transport of goods will not decrease in the future, quite the contrary. All in all, this will lead to a lower energy demand, with electricity accounting for the largest proportion, while the energy supply from fossil sources will decrease significantly.

	L 0,				
	useful energy			final energy	
Trends	electricity	heating/ cooling	traction	electricity	Fossil energy
demographic change	<u>ل</u> ا	۲ ۲	Ŷ	₩	۲ ک
climate change	-	仓	-	仓	-
energy efficiency directive	۲	۲	-	۲	۲a M
building refurbishment	-	û	-	A	û
freight traffic	-	-	仓	仓	2
power-to-heat	-	-	-	仓	Û
electromobility	-	-	-	仓	Û

Tab. 1: Trends and their impact on useful and final energy demand until 2050

With the help of the trends mentioned in Tab. 1, an estimate of the future useful energy demand (Fig. 1) and final energy demand (Fig. 2) was generated.



Fig. 1: Useful energy demand 2020 - 2050

At first glance, the useful energy demand will hardly change: from the current level of slightly more than 40 TWh, the useful energy demand will drop by about a quarter by 2050. The drivers here are demographic change and the various energy efficiency measures. The proportions of classic electricity applications, process heat and traction will remain almost unchanged. However, the proportion of space heating demand decreases significantly due to building renovation measures, while the demand for air conditioning increases at the same time.

The final energy demand shows a completely different picture. Here, the proportion of electricity has more than doubled from the current 20 percent to 44 percent, with a slight increase in the absolute amount of energy. The fossil energy sources coal, oil and natural gas are declining accordingly. While natural gas will still play a role in industrial processes and, to a lesser extent, for heating buildings in 2050, mineral oils will be used almost exclusively in the transport sector, which has not yet been electrified. Hard coal and lignite no longer play a role in 2040 due to the coal phase-out agreed for 2038. The final energy source "renewables" is dominated by solid biomass in the form of firewood and wood pellets, followed by solar and geothermal energy. The liquid or gaseous hydrocarbons that will still be needed by some energy converters in 2050 do not necessarily have to be of fossil origin. Power-to-X technologies can already provide climate-neutral fuels (Power-to-Liquid) or fuel gases (Power-to-Gas) today.



Fig. 2: Final energy demand 2020 - 2050

It can also be seen that in 2050 only 30 TWh of final energy would have to be used to provide 31 TWh of useful energy. This paradoxical ratio results from the strong integration of geothermal or ambient heat by means of PtH technologies, especially heat pumps. However, geothermal or ambient heat is not included in the final energy statistics.

To sum up: In the next 30 years, the demand for transport and heat as well as the demand for mechanical work and thermal energy in industrial production processes will continue to exist. However, there will be a fundamental change in the energy sources through whose conversion these benefits are generated: away from fossil energy sources towards renewably generated electricity and possibly also "green" fuels.

The demand for useful energy is generated by all sectors: The industry sector generates a demand for building heating, process heating, air-conditioning and process cooling, a demand for electricity for classic electricity applications as well as material use. In the commercial//retail/services sector, the material use is omitted, and in the household sector, process heating and cooling are omitted. The transport sector is divided into freight and passenger transport and quantified in passenger-km and ton-km.

3. Energy system modell

What is the best way to meet this final energy demand in 2050? To answer this question, a model of the Thuringian energy system was created. Energy system models are computational programs that determine how a given energy consumption can be covered at any given time by different generation, storage and sector coupling technologies, so they calculate an optimal interaction of the different technologies. Energy consumption and generation patterns as well as prices are available in an hourly temporal resolution². The energy system can be optimized with respect to a predefined criterion. These can be, for example, minimum costs or CO₂ emissions.

The energy system model Thuringia was modelled with the open energy modelling framework oemof (oemof 2021) hourly-resolved for 1 year. Oemof is a framework implemented in Python, which can be used to solve linear problems with an open source solver. The object-oriented library solph was used, which is structured in blocks: There are sinks, which is the load, i.e. the demand that has to be covered. It can be covered by sources, by imports, self-generation i.e. renewable energy production and/or storage discharge. All sources are connected to the sinks via so-called buses, which serve as a busbar for each energy source. So there is a bus for electricity, one for heat, etc. In the model, each energy carrier - i.e. each different "bus" - is shown in a different color. The connecting link is formed by sector coupling technologies i.e. PtX, when, for example a heat pump converts electricity from the electricity bus into heat, which is fed to the heat bus. There is also storage that can store energy from a bus. For each technology, there is a block in which all photovoltaic systems, for example, are grouped together. The use of the individual options is controlled by an optimization criterion, like minimum costs. Fig. 6 shows the model of the energy system. The individual input data will be discussed below.

 $^{^{2}}$ For the energy prices, data from an external service provider was used, which provides price time series up to 2050 via a merit order model of the European electricity market (brainreport 2019).

For implementation in the model, the useful energy demand per sector is calculated with standard load profiles, as shown in Fig. 3. The load profiles are scaled with the corresponding energy consumption for the analysis year. The electricity demands in green, red and brown and processes gas / process heating in purple have a weekday-dependent pattern, while room heating demands in blue and orange depends on the outdoor temperature and the seasons. The useful energy is provided by converters, which cause a final energy demand. The final energy demand for each energy source is summed up as a total load. These loads are shown on the bottom right of Fig. 6.



Fig. 3: Standard load profiles

As a transit state, Thuringia can import electricity, gas, oil, coal, etc. beyond its federal state borders (shown in the bottom left of Fig. 6), and also export them again (shown in the top right of Fig. 6). For this purpose, prices for the fossil energy sources are deposited. For electricity, a time-resolved price time series is used, which is correlated with photovoltaic and wind feed-in profiles, so that the electricity price is low when there is a lot of PV or wind in the grid (Fig. 4). Grid usage fees are also taken into account.



Fig. 4: Electricity import price, hourly resolved time serie

Furthermore, the energy demand is covered by generation from renewable energies. These are listed in the model to the right of the natural gas bus. For wind power and photovoltaics, feed-in profiles are also stored, as showed in Fig. 5 for photovoltaics for 4 different planning regions for a period of 2 weeks, so that one peak at midday can be seen for each day. It is also possible to use solar thermal energy. Furthermore, hydropower can be used, the output of which is fixed because the entire potential has already been used in Thuringia. Biogas substrate can be converted into electricity and heat in a CHP plant, solid biomass (e.g. wood) can also be used for electricity or heat production - with



Fig. 5: Photovoltaic feed-in profiles for Thuringia's planning regions for 2 weeks





Sector coupling or PtX technologies (to the left of the renewables and at the bottom center of the model) offer the possibility of feeding biogas into the natural gas grid. Hydrogen can also be fed into the natural gas grid up to a certain percentage. PtH options include integrated air and terrestrial heat pumps and electrode heating elements. There are stationary fuel cells with which electricity can be generated from hydrogen if the reverse technology electrolysis has previously produced the hydrogen from electricity as a PtG technology. Another PtG technology is methanation, whereby methane is produced from hydrogen and fed into the natural gas grid. Last but not least, PtL can also be used to produce synthetic fuel from hydrogen. The material use to the left of the PtX technologies is industry.

Electricity storage facilities are available, including lithium-ion storages, sodium storages and pumped storage power plants, as well as heat, hydrogen and gas storages. In the model, these can be seen to the right of the renewables.



Various parameters are included in the model, for each technology investment costs (so Capital Expenditures), operating and maintenance costs (so Operational Expenditures) and Efficiencies, which are mainly taken from the dena study (dena, 2018), where these parameters were determined for the whole of Germany. In addition, regional potentials (i.e. capacity limits) are specified for each technology. Fig. 7 illustrates the potential of photovoltaic free field for the four planning regions of Thuringia. There is significant potential along the federal motorway (in orange) and the railway tracks (in black). Some potentials are limited, such as that of wind power to 1 % of the state area of Thuringia. The other restrictions are those already mentioned in the Thuringian Climate Act, which prescribes reductions in greenhouse gas emissions and sets CO_2 budgets for each year on the basis of this: In 2030, a maximum of 9 million tons of CO_2 may still be emitted, in 2040 6 and in 2050 only 1.5 million tons of CO_2 . In addition, the question was addressed of what a climate-neutral energy system with 0 CO_2 emissions would look like. The condition "balance renewable" is also mentioned here, or the 55 % of renewables in the electricity demand in 2030.



Fig. 7: Potential of photovoltaic free field

4. Scenarios

Two scenarios were modelled: Scenario B is the baseline scenario. It has conservative assumptions regarding renovation rate, energy efficiency and openness towards PtX technologies. It also assumes no hydrogen demand. A CO₂ price is applied to the import of fossil energy sources, and only the fossil share to the import of electricity. The CO₂ price is approx. 80 ϵ /tCO₂ for 2030, approx. 110 ϵ /tCO₂ for 2040 and approx. 120 ϵ /tCO₂ for 2050. Another assumption is that from 2050 onwards, electricity imports, i.e. the German electricity mix, will be CO₂-free and will no longer be subject to the CO₂ price.

In contrast, the innovative scenario A assumes increased efficiency, more PtX and a higher renovation rate, and thus a lower energy demand than in the baseline scenario. Scenario A also includes hydrogen-based mobility and therefore a hydrogen load.

The years 2030, 2040 and 2050 were modelled.

5. Results

This chapter describes which technologies are needed with which output in order to obtain a cost-optimal energy system under all the conditions mentioned. The first technology is wind power, as shown in Fig. 8. On the y-axis, the power is plotted over the years shown on the x-axis. 2050 "c" here stands for a climate-neutral energy system in 2050, i.e. 100 % CO₂ reduction. In the case of wind power, the basic scenario B in blue and the innovative scenario A in orange are both above the potential limit in red dashed lines, which means that the full wind power potential will be exploited as early as 2030, which corresponds to a tripling of the current capacity.

A higher capacity is also required for photovoltaics (Fig. 9), approx. 7-8 times as much as at present, especially in the year 2040, from which the condition applies that the entire energy demand must be covered by renewable energies on balance. However, the potential limits of fallow land and roadside areas are not reached. The fact that so much PV is needed in 2040 means that less electricity has to be imported, as can be seen in 10. In the innovative scenario A, on the other hand, less PV is needed compared to the conservative scenario B, and instead more electricity is imported to meet demand.



There is also generation from hydropower plants, which, as already mentioned, is at a constant 31 MW capacity, because the potential has already been reached.

Electrode heating elements (Fig. 11) are increasingly used as a sector coupling technology. Large-scale heat pumps (Fig. 12) are no longer used in 2050³. The energy demand decreases over the years due to the factors mentioned at the beginning, which is why the energy demand is still highest in 2030; in 2050, the energy demand has decreased to such an extent that electrode heating elements are sufficient.

As far as biotechnologies are concerned, a more complex picture emerges in Fig. 13, which is only shown for the baseline scenario B, as in the innovative scenario A the relevant results are the same. In blue, the electrical output of the biogas in combined heat and power (CHP) is shown, which decreases over the years, as does the electrical output of the combined cycle gas turbine (CCGT) in CHP in purple. At the same time, the capacities of the biogas feed-in, of existing and new plants in both shades of green, increase, as does the capacity of the gas storage facility in orange, which is the only one related to the secondary axis on the right. In 2050, with little or no import of fossil gas, especially in the climate-neutral scenario, the gas storage is used for biomethane processed from biogas, not for fossil gas. A change in the use of biogas is thus emerging, away from pure electricity and heat production towards a substitution of natural gas.



Fig. 13: Bio- and gas technologies

As storage technologies, electricity storage technologies are needed. Here, sodium storages (Fig. 14) are preferred to lithium-ion battery storages, and ever larger capacities are needed. In the case of pumped storages, only the existing capacity is used permanently. The demand for heat storages (Fig. 15) also increases over time. In the

³ Large-scale heat pumps supply district heating networks. Residential heat pumps are widely used and not subject to optimisation. Their electricity demand is part of total electricity demand.

innovative scenario A, it can be seen that the heat demand in 2050 decreases compared to 2040, due to the higher renovation rate than in the conservative scenario B. However, in order to achieve the goal of climate neutrality, more heat storage capacity is needed again than without. The need for gas storage (Fig. 16) increases, as already mentioned, and can be seen here again for both scenarios. Hydrogen storages (Fig. 17) are needed in innovative scenario A in 2050, in connection with electrolysis, because innovative scenario A assumes hydrogen-based mobility.

Finally, costs and emissions can be compared. Fig. 18 shows the total costs. 100 % represent the costs of the conservative baseline scenario B in 2030. The other costs are shown in relation to this. It can be seen that the costs decrease because the energy demand to be covered also decreases. If Thuringia is to become climate-neutral, the total costs are again somewhat higher than if only 95 % CO_2 is to be saved. The innovative scenario A is more beneficial than the conservative one because, on the one hand, a lower energy demand has to be met and, on the other hand, a different composition of PtX technologies is assumed to generate the useful energy demand.

The emissions shown in Fig. 19 also decrease. Again, 100 % are the emissions of the conservative baseline scenario B, the other emissions are shown in proportion. The potential limits are the climate policy restrictions, i.e. the CO_2 budgets calculated on the basis of the savings potentials. Again, this shows that emissions are falling and do not even reach the CO_2 limit, except in Scenario B 2050 with the 95% savings target. The emissions of the innovative scenario A are always lower than those of the base scenario B. The last entry stands for climate neutrality, so that 0 emissions are emitted.



6. Summary

Some technologies are needed immediately and with high output, such as wind power, photovoltaics and electricity storages. Other technologies need to be continuously expanded, including electrod heating elements, heat and hydrogen storages including electrolysis, but also gas storages. The last mentioned are also undergoing a change of use, with biomethane being stored in them instead of natural gas. The change of use is biogas, which is no longer used for electricity and heat production, but is processed for injection into the natural gas grid. Some technologies are less used, including large-scale heat pumps, assuming that there are more electrode heating elements, and the CCGT, which is made redundant by the other gas use. Unused technologies are solar thermal energy (whereby however existing plants were not taken into account) hydrogen injection into the natural gas grid, PtL from hydrogen, methanation from hydrogen, and stationary fuel cells.

The prices for the provision of final energy remain at a comparable level and the CO_2 price and energy efficiency measures ensure compliance with the climate policy boundary conditions in 2030 and 2040. If the innovative scenario comes into effect, both costs and emissions will decrease significantly.

Further scenarios were calculated, which illuminate the effects of a different CO_2 price, include a higher wind power potential, as well as studies on energy self-sufficiency, solar thermal energy and electricity storages. They are published together with all information about the anticipated development of demands, costs, efficiencies and other technological parameters (in.RET, 2021).

7. Acknowledgments

This paper is based on the research project on energy system modelling of Thuringia, for the development of statespecific detailed models, funded by the Thuringian Ministry for the Environment, Energy and Nature Conservation, as a sub-project within the project "ZO.RRO -Zero Carbon Cross Energy System", funded by the German Federal Ministry for Economic Affairs and Energy under the funding code: 03ET4080A. The authors are responsible for the content of this publication. The contents presented here are only a part of the overall project and are not to be understood as a project result.

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A-02. Societal Changes/Perspectives/Issues

The EU Clean Energy Policy under the European Green Deal and COVID-19 pandemics – how the renewables historically won the majority share in the EU's electrical energy mix

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Abstract

The paper presents a regional case study of the European Union's clean energy policy impact on the European electricity market transformation reaching a tremendous milestone for the EU as confirmed by the European Commission's Directorate-General for Energy (ENER) on 9th April 2021 – the renewable energy sources for the first time in the history overcoming the combined fossil fuels in electrical energy generation mix of the year 2020. This achievement, although influenced by exceptional circumstances of the COVID-19 pandemics and the electricity demand shock, is primarily an effect of the Clean Energy for all Europeans Package implementing the European Green Deal strategy designed to position the EU as a global leader in the green transformation, leading by example and turning climate challenges into a growth opportunity, as such presenting optimistic policy perspective for a global transformation towards a 100% renewable energy world, thus mitigating dire threats of the global warming by drastically cutting greenhouse gases emissions.

Keywords: European Green Deal, EU energy policy, renewable energy sources in electricity generation

1. Climate change drivers for the European clean energy transformation

In view of the scientific consensus for the global warming and induced climate change with dynamic weather patterns influence, confirmed among others by the scientific evidence based Paris Agreement's declarations of 2015, it becomes clear that the longer no action is taken, the more difficult and more expensive it becomes to reach the emission and climate goals at estimated temperature targets to counter this serious situation.

It has been concluded by multiple analyses that without an action taken on the climate change, the EU will experience, during the lifetime of our children, unbearable social and economic costs. Europe notes ca. 400 thousand premature deaths per year today due to air pollution (cf. Air quality in Europe by the European Environment Agency, 2019). In regard to weather patterns dynamic shifts the impact is also overreaching with multiple induced natural disastrous events including unprecedented heatwaves, fires, droughts and floods. In Europe alone in the recent few years there have been noted ca. 90 thousand annual deaths as a result of heatwaves (cf. European Commission's Joint Research Centre PESETA IV). About 16% of species were assessed at risk of extinction at 4.3°C temperature increase (as estimated by Missirian and Schlenker in 2017). According to the same authors there is already 40% less available water in southern regions of the European Union, while on the other hand as much as 0.5 million of people in Europe are now exposed to river flooding each year and as much as circa 2.2 million people are exposed to coastal inundation each year.

In regards to the climate change induced by the global warming, carbon dioxide levels are predicted to double by the year of 2030 with Europe's temperature expected to increase by 2-3 °C in the summer season (cf. European Environment Agency - Problems - April 2016). Accordingly to the same study Europe is responsible for nearly one third of the world's gas emissions that deplete the ozone. More than 50% of all surface area where ecosystems are in Europe are presented with threats from climate change induced management problems and stresses. On average, 700 thousand hectares of woodland are burnt by fires each year in the EU, leading to the degradation of the European forests and further diminishing the natural ecosystems CO_2 absorption rates. Other studies (International Resource Panel - Global Resources Outlook - 2019) have also shown that on the scale of the last 50 years the world's annual extraction rate of fossil energy resources has tripled, which in consequence has been estimated as leading to as much as 90% loss in biodiversity. The European Union's industrial sector is responsible for circa 20% of the total European greenhouse gases emissions (cf. European Commission - EU Climate Action Progress Report – 2019). With about 50 thousand of industrial locations in the EU, up to \notin 189 billion is spent on health issues related to pollution from these installations (cf. Schaible, 2020).

Further 25% of the European greenhouse gas emissions come from the transportation sector. Road transport clearly dominates in emissions, taking 71.7% of the total figure, followed by 13.9% from aviation, 13.4% from water transport, along with railways and other transportation branches accumulating the remaining part (European Commission – Sustainable mobility – 2019).

The progress of electrification of cars, dynamically scaling in Europe is thus a major contribution to the green transformation providing the electricity generation mix involves dominating share of the clean renewable energy sources. In Europe the demand for electrically chargeable vehicles (ECVs) has grown impressively throughout 2020 despite the pandemic induced crisis, with almost 0.5 million of new ECVs registered in the EU at large (marking the highest figure so far and resulting with an unprecedented 17% market share, which is over 2 times higher as compared to China and over 6 times higher as compared to the United States).

The climate system of our planet is complex, strongly interdependent and by no means easily simulated. Decades spanning observations noting unusual weather escalations getting more frequent in the recent years show that the global warming might induce a climate destabilization that can possibly scale very profoundly in a feedback loop of complex interdependent factors, which when set in motion might be difficult to stop. This is a well-known property of very complex, interdependent systems.

The 2021 Nobel Prize in Physics has been awarded to climatologists Syukuro Manabe of Princeton University, Klaus Hasselmann of Max Planck Institute for Meteorology, and physicist Giorgio Parisi of Sapienza University for their groundbreaking contributions to our understanding of complex physical systems, for the discovery of the interplay of disorder and fluctuations in environmental systems from atomic to planetary scales as well as for setting foundations for physically modelling the Earth's climate, quantifying variability and reliably predicting global warming.

Although the sheer economics of the climate change and destabilization is a strong factor driving the clean energy change, notably in Europe, it is hard to measure in money the values such as health and wellbeing of mankind's next generations, as well as of animals and ecosystems. Beyond such economically unmeasurable threats for the future of the life on our planet, as much as ca. €190 billion annual losses were projected for a 3° C increase in global average temperature (cf. Ciscar et al., 2014). Globally, the number of people at risk of being forced from their homes by river flooding could increase to 50 million a year (cf. Internal Displacement Monitoring Centre, Assessing the impacts of climate change on flood displacement risk, 2019) and the climate change could lead to at least 20% food price rise in 2050 (COACCH, The economic cost of climate change in Europe, 2018). It has been also estimated that there will be ca. 660 thousand of additional asylum applications per year in the EU at 5°C temperature increase (Missirian and Schlenker, 2017). Economic costs of the heat-related mortality could amount to more than €40 billion per year (cf. COACCH).

The dominating role of energy is confirmed by more than 75% of greenhouse gas emissions being related to the production and use of energy within the EU (cf. European Commission - Clean Energy, 2019). Thus the general reasons for the European Green Deal and the clean energy transformation are based upon the environmental issues (such as climate change, loss of biodiversity, ozone depletion, water pollution or waste production) but also as much upon their economic consequences.

The strategy in continuing Europe's previous sustainable growth assuring clean energy policies of the EU has turned out successful – with the hallmark of the renewables winning electricity mix share over fossil fuels in the EU was based on the renewable resources providing for 17.5% of the EU's overall gross energy consumption in 2017, while simultaneously stimulating economic growth of the EU's green energy sector.

The paper discusses the progress of the EU's clean energy transformation along with the climate change drivers for the European clean energy transformation policy and the European Green Deal implementation, which have recently resulted in the historic for the EU renewable energy dominating share in the electrical energy generation mix for 2020.

2. The EU climate and energy policy context

Europe has a strategic ambition to become the first climate-neutral continent by the year 2050. In previous European climate strategies and goals, the EU has set out on a path to gradually reduce its greenhouse gas emissions. The most important climate and energy goals were defined in the 2020 climate and energy package and in the 2030 climate and energy framework. These goals were set in order to put the EU on a road to a climate neutral economy, as described in the long-term strategy 2050 and proposed in the form of the European Climate Law. The EU is tracking its progress in reducing emissions through regular monitoring and reporting, reviewing and constantly adjusting its policies towards the goal of becoming a climate resilient society by 2050, fully adapted to the inevitable effects of the climate neutrality was set out in the EU Strategy on Climate Adaptation. The 2020 policy package defined a set of laws that needed to be passed in order to ensure that the EU meets its climate and energy goals for 2020. The package contained three main objectives: 20% less greenhouse gas emissions (compared to 1990 levels), 20% of EU energy from renewable sources, 20% improvement in energy efficiency.

These goals were set by leaders of the EU in 2007 and implemented into law in 2009. The EU has taken action in a number of areas to ensure that these objectives were successfully achieved. These efforts had particularly concerned establishment of the Emissions Trading System (ETS) as a central instrument for reducing greenhouse gas emissions from large-scale plants in the energy and industrial sectors as well as in aviation. In 2019, the ETS covered around 40% of total EU emissions (excluding international aviation). In 2020, the target was set that emissions from these sectors should be 21% lower than in 2005. Another aspect of this effort were the national emission reduction targets. These targets covered the burden sharing sectors (i.e. non-ETS and no agriculture), which constitutes approximately 60% of the total EU emissions (also excluding international aviation) in 2019 – such as non-ETS industry, housing, agriculture, waste and traffic (excluding air traffic). As part of the so-called effort-sharing decision, the EU countries have set binding annual targets for reducing emissions in these sectors by 2020 (compared to 2005).

These goals were set to vary accordingly with national prosperity and wealth levels - from a 20% reduction for the richest countries to a maximum of 20% increase for the least prosperous countries (although these member states will need to make efforts to limit emissions) by 2020. Progress on NERT is monitored every year by the Commission, with each country being obliged to report its emissions.

The EU has also included the renewable energy targets at national level. In this initiative, the EU member states have set binding national targets in order to increase the share of renewable energies in their energy consumption by 2020 within the framework of the Renewable Energy Sources Directive. These targets varied to reflect different countries' starting points for renewable energy production and their ability to increase it (e.g. from 10% in Malta to 49% in Sweden). The overall effect allowed the EU as a whole to meet its 20% target for 2020 (more than double the 2010 level of 9.8%) and a 10% share of renewable energy in the transport sector.

The innovation funding programs in the 2020 package have proven to be taking the decisive role. The EU supported the development of low carbon technologies through many programs, e.g. the NER300 program for the renewable energy technologies and carbon capture and storage, as well as through the Horizon 2020 funding for research and innovation programs along with several other EU co-funded programs run by dedicated networks as well as programs cofounded by the European funds at national levels.

Part of the effort was also aimed at energy efficiency, and measures to increase these were set out in the Energy Efficiency Directive. Achieving the 2020 package goals has helped to increase the EU's energy security as well, by reducing dependence on traditional energy imports and contributing to the development of the European Energy Union (also creating jobs and promoting green growth, while making Europe more competitive globally in renewable energy technologies).

The Commission's proposal, following the 2020 package, to reduce greenhouse gas emissions by at least 55% by 2030 has set Europe on a road towards becoming climate neutral by 2050 in undertaking a globally leading role in responsibility for the planet.

On the basis of a comprehensive impact assessment, the European Commission proposed to expand the EU's

ambitions to further reduce greenhouse gases emissions and continue on this more ambitious path for the subsequent 10 years. Undertaken evaluations have shown in what ways different sectors of the economy can contribute and defined policies needed to support these actions. Objectives include setting a more ambitious and cost-effective path to climate neutrality by 2050, promoting green job creation and maintaining the EU's track record in reducing greenhouse gas emissions while growing the economy and encouraging international partners to share their ambitions for limiting the rise in global temperatures to 1.5 °C and to avoid the most serious consequences of the climate change.

The 2030 climate target that the Commission proposed in increasing the EU's ambitions to reduce greenhouse gas emissions by 55% below 1990 levels by 2030 was a substantial increase compared to the previous target of at least 40% (cf. European Commission 2030 climate & energy framework). Raising the 2030 ambition supports policymakers and investors with certainty, so that decisions made in the coming years do not cut in emission levels inconsistently with the EU's goal to become fully climate-neutral by 2050. This proposal delivered on the commitment made in the Communication on the European Green Deal to put forward a comprehensive plan to increase the European Union's target for 2030 towards 55% in a responsible way. It is also in line with the Paris Agreement (2015) objective to keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5 °C. The impact assessment (European Commission, Stepping up Europe's 2030 climate ambition, September 2020) accompanying the proposal prepared the ground for adapting climate and energy policies to help decarbonise the European economy. This includes determining the future role of carbon pricing and its interaction with other policies. The European Commission launched legislative proposals on how to achieve these objectives. It declared to be reviewing and revising all relevant policy instruments to achieve the additional emission reductions.

In October 2020, the European Commission published inception impact assessments, followed in November 2020 by the four open public consultations to prepare these revisions: 1) EU Emissions Trading System Directive (European Commission, Updating the EU Emissions Trading System ETS, November 2020), 2) Effort Sharing Regulation (European Commission, National emissions reduction targets – review based on 2030 climate target plan, November 2020), 3) Land Use, Land Use Change and Forestry Regulation (European Commission, Land use, land use change & forestry – review of EU rules, November 2020) and CO₂ standards for cars and vans Regulation (light-duty vehicles - CO₂ emissions for cars and vans – revision of performance standards, November 2020).

Furthermore, the Climate Law Regulation, proposed by the European Commission in March 2020 and finally adopted on 9th July 2021 (European Commission, European Climate Law, July 2021), aimed to incorporate into the EU law the 2050 climate-neutrality target agreed by EU leaders in December 2019 and set the direction for all EU policies. In September 2020, the Commission proposed to include the increased 2030 target in the mentioned regulation as a whole by co-legislation under the ordinary procedure. The new 2030 target also formed the basis of discussions on revising the EU's nationally determined contributions of the individual member states to reducing emissions under the Paris Agreement.

As the 2030 climate and energy framework included EU-wide targets and policy objectives for the period from 2021 to 2030 it has been an important part of the European Green Deal, that the European Commission proposed in September 2020 to raise the 2030 greenhouse gas emission reduction target, including emissions cut to the mentioned value of at least 55% compared to 1990. The European Commission has assessed actions required across all sectors, including increasing energy efficiency and deployment rates of renewable energy, as well as started the process of making detailed legislative proposals to implement and achieve these increased ambitions. The strategy to move Europe as a whole continent towards a climate-neutral economy is very part of the Paris Agreement and stimulating in terms of leading by example the international cooperation in this regard. The key targets for 2030, beyond the mentioned 40% cuts in greenhouse gas emissions (from the 1990 levels) also featured at least 32% share for renewable energy and at least 32.5% improvement in energy efficiency. The 40% greenhouse gas target is to be implemented by the EU Emissions Trading System, the Effort Sharing Regulation with Member States' emissions reduction targets and the Land Use and Forestry Regulation. In this way, all sectors will contribute to the achievement of the target by both reducing emissions and increasing efficiencies. All three pieces of climate legislation will be continuously updated with a view to implement the proposed at least 55% net greenhouse gas emissions reduction target. The Commission came forward with the proposals in summer 2021.

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Under the Regulation on the Governance of the Energy Union and the Climate Action, the EU has hence adopted integrated rules to ensure planning, monitoring and reporting of progress towards its 2030 climate and energy targets and its international commitments under the Paris Agreement. Based on the better regulation principles, the governance process involves consultations with citizens and stakeholders.

Summarizing, the EU aims to be climate-neutral by 2050 – that is to form an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement.

The transition to a climate-neutral society is both an urgent challenge as well as a great opportunity to build a better future for all and to secure highly competitive position globally for the European Union. All parts of society and economic sectors will take a role in this endeavor – from the power sector to industry, as well as transport, buildings, agriculture and forestry. The EU can lead the way by investing into innovative but realistic technological solutions, empowering citizens and aligning action in key areas such as industrial policy, finance and research, while ensuring social fairness for a just transition, supporting highly impact regions (e.g. coal or heavy-industry regions).

The European Commission has articulated its vision for a climate-neutral EU back in 2018 (European Commission, A Clean Planet for all - a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, November 2018), looking at all the key sectors and exploring possible paths towards the green transition. The European Commission's vision covered all EU policies and was strictly in line with the Paris Agreement objective to keep the global temperature increase to well below 2° C and pursue efforts to keep it up to 1.5° C. As part of the European Green Deal.

All Parties to the Paris Agreement were invited to communicate by 2020 their mid-century, long-term greenhouse gas emission reduction strategies. The European Parliament endorsed the net-zero greenhouse gas emissions objective in its resolution on climate change in March 2019 (European Parliament resolution of 14th March 2019 on climate change – a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy in accordance with the Paris Agreement 2019/2582-RSP, March 2019) and resolution on the European Green Deal in January 2020 (European Parliament resolution of 15th January 2020 on the European Green Deal 2019/2956-RSP, January 2020).

The European Council endorsed in December 2019 the objective of making the EU climate-neutral by 2050 (European Council, Conclusions on climate change, the MFF, the Conference on the Future of Europe, EU relations with Africa, the WTO, Turkey and Albania, 12th December 2019). The EU submitted its long-term strategy to the United Nations Framework Convention on Climate Change (UNFCCC) in March 2020 (United Nations, Long-term low greenhouse gas emission development strategy of the European Union and its Member States, 6th March 2020). Under this strategy the EU Member States are required to develop their own national long-term strategies on how they plan to achieve the greenhouse gas emissions reductions needed to meet their commitments under the Paris Agreement and the EU objectives (European Commission, National long-term strategies – EU countries' long-term strategies to meet their Paris Agreement commitments and the energy union objectives, 30th September 2021).

3. Introducing the European Green Deal

The European Green Deal is a package of political initiatives of the European Commission with the strategic goal of transforming Europe to fully climate neutral by the year 2050.

Along the lines of the Emissions Gap Report 2020 by United Nations Environment Program, meeting the Paris Agreement target of a 1.5 °C temperature increase with a probability of 66% requires 57% global emission reduction of CO₂ from 2019 to 2030 and therefore well above the preceding policies with 40% of the EU target as described in the previous chapter. In this way, the European Green Deal has been complemented with an impact assessment plan for increasing the EU's greenhouse gas emissions reduction target by 2030 to at least 50% and up to 55% compared to 1990 levels. In the context of the Paris Agreement, and therefore using today's emissions as a benchmark, since EU emissions have already decreased these levels by over 30% since 1990, the 55% reduction target, using 1990 as reference value, means in terms of 2019 reference, a 40% reduction target.

This emission reduction target of 57% by 2030 represents average global reductions, while advanced economies are already for over 20 years proven in necessity to make a greater contribution (Heil, M., Wodon, Q., 1997).

The plan for the European Green Deal implementation is thus to review each existing law in the EU in terms of its climate benefits as well as to review economy in this regard, along with the issue related sector-specific policies such as renovation of buildings for energy efficiency, biodiversity, agriculture and innovation.

European Commission President Ursula von der Leyen indicated the European Green Deal was Europe's man on the Moon moment as the plan would make Europe the first climate-neutral continent. Von der Leyen has appointed Frans Timmermans as the Executive Vice President of the European Commission for the European Green Deal. On December 13, 2019, the European Council decided to push the initiative forward (with an optout for Poland however). On January 15, 2020, the European Parliament has also voted in support of the agreement and called for undertaking even higher ambitions in regard to the climate change.

The European Green Deal aims to improve people's wellbeing by making Europe climate neutral and hence protecting a natural ecosystem of Earth's climate proposing a solution for an existential threat for people, our planet and the economy due to the climate change caused by the currently scientifically proven and undisputed global warming. The EU will become climate neutral by 2050 to protect the life on Earth for all humans, animals and plants by reducing greenhouse gas emissions and pollution. It will also help European companies become world leaders in clean energy, products and technologies, hence positioning Europe with a competitive edge for the new economy, with an aim to overturn the challenge of the clean transition into an economic opportunity.

As much as 93% of Europeans see climate change as a serious problem and a similar percent of Europeans have taken at least one action to counter the climate change on their own. About 79% agree that action against climate change will lead to innovation and development. The European Green Deal is about climate and energy, and for most, the European Green Deal is a strategic policy to ensure a fair and inclusive transition for Europe to clean energy, as energy from traditional fossil fuels plays a role in the challenges global warming introduces. Yet another important goal of the European Green Deal policy is to turn the challenge into an opportunity and to base a new dynamic economic growth in Europe on the transformation towards 100% clean energy.

The European Green Deal is thus planned as a new growth strategy for the whole Union. It is meant to help cut emissions while creating jobs and advancing the clean energy industry to place EU in the forefront of innovation where the global market uptakes clean energy technologies. It is also meant to propose an inclusive transition securing life on Earth as we know it for the generations to come. Accordingly with the objectives of the European Green Deal the EU will be climate neutral in 2050 to assure the above.

On the way towards this strategic objective, the European Commission has proposed a legal framework called the European Climate Law that makes political engagement transformed into a legal obligation and a legal framework of incentives for the investments. Achieving this goal requires action from all sectors of the European economy: energy (decarbonizing the energy sector - the generation and use of energy accounts for more than 75% of the EU's greenhouse gas emissions), buildings (renovating buildings to support citizens in cutting their energy bills and their energy consumption - buildings account for circa 40% of the energy consumption in the EU), industry (helping industry to innovate and leading the global green economy, European industry currently uses only 12% recycled materials), mobility (making it cleaner, cheaper and healthier within both private and public transport - transport accounts for circa 25% of the EU emissions). With these actions the European Green Deal is projected to improve health of citizens now and in the future.

In a nutshell, the strategy has two objectives: clean and efficient energy (including clean energy, better alternatives to public transport and the transition to electrification, development of electromobility and charging infrastructure for transport with electric vehicles, renovated houses, schools and hospitals in terms of energy efficiency) and less impact on the environment for health and wellbeing (towards assuring the clean air, water and soil, reusable or recyclable packaging, less waste, less pesticides and fertilizers, healthier food, more environmentally friendly products in EU stores for better health for present and next generations).

Preparing a large-scale policy for the climate-neutral, circular economy on a continental scale is an ambitious
and difficult task. To become the first climate neutral continent by 2050 will require huge investment from both the public and private sectors. Public finances will lead the way with private actors following and providing the benchmark for the policy success.

The European Green Deal's investment plan involves mobilizing of at least €1 trillion of investments over the course of 10 years, thanks to the combined: capital from EU and national budgets, public and private investments, additional measures to facilitate and boost green public and private investment, attractive investment conditions, technical assistance to help investors in selecting sustainable projects. Further funding channels involve: 30% of InvestEU to projects that fight climate change, 25% of all European Union funding for climate measures, Stimulating green investments with support from the EIB Group

As part of the Sustainable Europe Investment Plan, the Just Transition Mechanism will mobilize at least $\in 100$ billion over the period of 2021-2027, to provide targeted support to regions, workers and sectors that are most affected by the transition towards the green economy. The EU will provide financial support and technical assistance to help those that are most affected by the move towards the green economy.



Fig. 1. European Green Deal funding scheme. The numbers shown here are net of any overlaps between climate, environmental and Just Transition Mechanism objectives. Source: European Commission

In terms of competition it should be stressed that all those acting first and fastest will also secure the advantage of the ecological turnaround. But public finances alone will not be enough.

It is well understood on the level of the EU Commission that there is a need to unlock private investment by setting green and sustainable finance at the center of the EU investment chain and financial system. For the EU the pursued transition to the climate-neutral economy on a level of a continent, it is critical that the political commitment must be accompanied by a huge scale investment.

The European Green Deal shows the determination in Europe to fight the climate change, which is currently being underpinned with a financing plan. In opinions of the policy makers, similarly as the European Union was not built overnight, the new green Europe will also not come to be in a matter of day. Setting sustainability in clean energy at the center of the EU investments requires joint efforts on the level of policy and industry. The European Green Deal aims to facilitate it.

It should be also stressed another important aspect, i.e. the need to show solidarity with the most clean energy transformation policy involved regions in Europe, such as coal-mining regions and other industrial regions, to ensure that the Green Deal has a uniform support and its implementation is a common success.

The Just Transition Mechanism (JTM) is a key tool to ensure that the transition towards a climate-neutral economy happens in a fair way with solidarity involved and not leaving any region behind. It provides properly targeted support with a mobilization of at least \in 150 billion planned for the years 2021-2027 in most affected regions, to alleviate socio-economic impacts of the clean transition.

The JTM hence addresses both the social and economic effects of transition, focusing on the regions, industries and workers facing the greatest challenges, and mobilizing at least \notin 150 billion through the following 3 pillars: a new fund of \notin 40 billion for a just transition generating at least \notin 89-107 billion investment, the InvestEU Just Transition program mobilizing further \notin 30 billion in investment, the EIB public sector loan facility of \notin 10 billion in loans, additionally supported by \notin 1.5 billion from the EU budget to also mobilize \notin 30 billion in investment.

As part of its Green Deal commitment, the EU is fighting climate change not only through its ambitious internal policies but also through its close cooperation with international partners, as it is well understand that countering global warming must be a global effort.

Europe is determined to lead by example (it has already met its 2020 greenhouse gas reduction target and has presented a plan to cut emissions by at least 55% by 2030 and by 2050 it aims to become the first climate-neutral continent in the world) and motivate other developed countries to take responsibility, along with providing financial and technological support to the developing countries in clean energy transformation.

Climate protection is at the heart of the European Green Deal, which includes measures that range from an ambitious reduction in greenhouse gas emissions to investing in cutting-edge research and innovation to preserving Europe's natural environment - all this requires massive investment and differentiated efforts in relation to less and more effected regions, as well as energy and industrial centers.

The primary climate protection initiatives as part of the European Green Deal include: European Climate Law to anchor the goal of climate neutrality 2050 in the EU law, European climate pact to involve citizens and all parts of the European society in the climate protection effort, climate target plan for 2030 to further reduce net greenhouse gases - emissions by at least 55% by 2030, and the new EU strategy on adaptation to the climate change to make Europe a climate resilient society by 2050, fully adapted to the inevitable effects of pollution and the greenhouse effect.

At the international level, the EU will continue to conduct negotiations to increase ambitions of major emitters in the run-up to the United Nations Climate Change Conference in Glasgow (COP26).

4. The European Green Deal's implementation results

As the European Green Deal has been designed to position Europe as a global leader, leading by example on the global warming and the climate change front and to simultaneously turn the environmental challenge into a growth and economic recovery opportunity for the EU, the question to ask is what are its current results.

Answering this question, the immediate effects of the 2018 recast Renewable Energy Directive (2018/2001/EU) and other related clean energy policies under an umbrella of the European Green Deal, including the evolving Emission Trading System with emission caps on the EU level, the EU coal regions in transition initiative, the European Green Deal Investment Plan (with the Just Transition Fund, the InvestEU dedicated scheme of unprecedented scale of \in 1 trillion, the Modernisation Fund and the Innovation Fund, supported by Horizon R&D programme and the financial instruments of the Connecting Europe Facility and the European Investment Bank) influencing the clean energy transition economic and technical factors – have led to the coal and lignite electric generation falling in 2020 by as much as 22% (i.e. -87 TWh) and the nuclear output dropping by 11% (-79 TWh), with natural gas less affected due to its favorable prices (hence supporting coal-to-gas and lignite-to-gas switching) but still noting an annual drop of 3%.

This is an impressive result and a hallmark of the European Green Deal initial success.



Fig. 2: Solar energy share in electricity mix of the EU and reference countries in 2020, showing the EU reaching 5,2% share from just 0.08% share in 2006. Italy, Greece and Germany are leading the solar energy electricity-share race, all reaching impressing 9%, with Spain closely following (at almost 8%). The EU exceeded in this area both the US (3.2%) and China (3.4%). Source: chart by the author, based on statistical data by BP Statistical Review of World Energy & Ember.



Fig. 3: Competition between renewables and nuclear power share in electricity mix for the EU, with a crossing in 2013 (nuclear power is being phased down due to the risk of serious environmental impact in case of an incident, but is also considerably more expensive, currently estimated at 11 times more costly than photovoltaic energy, mainly due to necessary security investments – in the EU only France largely relies its electricity generation on nuclear power, with ca. 70% share stable for decades and renewables at ca. 23%). Source: chart by the author, based on data by BP Statistical Review of World Energy & Ember.

Meanwhile the rising renewable share in electricity generation in the EU was supplemented by ca. 29 GW of solar and wind grid deployments in 2020 (at levels comparable to those of 2019, proving that the pandemic did not strongly impact the renewable energy sources investments expansion, and as a matter of fact even supported its historical triumph in the European Union, by causing an overall electricity consumption drop).

These clean energy transition successes in the EU are certainly due to the current EU strategic policy and other factors, circumstances and actions, involving climate change drivers together with the estimated costs of not taking the action and the perspectives of the progress of the European Climate Law combined with the revision of the European Energy Law (including the European Commission's June 2021 scheduled recast of the Energy Taxation Directive, paying a close attention to the fossil fuel subsidies and tax exemptions).

The Directorate-General for Energy of the European Commission (ENER) confirmed in its communication of 9th April 2021 a historical success for the EU and the world at large. The share of electricity generated from renewable sources in the EU for the first time in the history exceeded the share of combined fossil fuels in 2020. The clean energy sources dominating share in the EU's electricity generation mix reached 39%, exceeding by 4% the combined share of fossil fuels amounting to 36%. It is an impressive result if taken into account that globally the electricity is generated at 63.3% from fossil fuels (excluding nuclear energy) and at 26.3% from renewables. The breakdown to different renewables in the electricity mix of the EU is presented on the Fig.1, showing an impressive growth rates of solar energy and wind power vs. a decline of fossil fuels.



Fig. 4: Electricity mix renewables share for the EU and reference countries in 2020, showing the EU reaching 39% share from 22% share in 2010. Source: chart by the author, based on statistical data by BP Statistical Review of World Energy & Ember.



Fig. 5.: The breakdown for energy sources in electricity mix for the EU in 2020 (showing decline in fossil fuels, e.g. the worst CO₂ and pollution emitter - coal from 30% to 13%, oil from 9% to 4%, gas on a stable level of below 20% after averaging – confronted with a steady growth of renewables: notably solar energy from 0.01% to 5.2% and wind power from 0.8% to 14.3%). Source: chart by the author, based on statistical data by BP Statistical Review of World Energy & Ember.

Although it is understood that decisive factors for achieving this breakthrough for the European Union in 2020 partially involved the exceptional situation of the COVID-19 pandemic and its overreaching impact on energy markets (the demand shock lowering the EU overall electric consumption level by 4% in comparison to 2019),

combined with the favorable weather conditions for the renewable energy and most notably for solar and hydro power, figures for the 4th quarter consumption levels (despite continued lockdowns in Europe) were getting closer to their usual values in contrast to the first 3 quarters of 2020 thus pointing towards normalization. This situation, in detail discussed in the Quarterly Report on European Electricity Markets (cf. EC's Directorate-General for Energy, unit A4, Market Observatory for Energy, April 2021), admits a well-justified expectation that the European Union is able to hold its newly gained ground in clean energy, especially as we observe how the European Commission's Clean Energy for all Europeans Package of policies (cf. CEP in references) gains momentum as the major pillar of the European Green Deal implementation.

Despite it being difficult to accurately estimate in quantitative terms on exactly what contribution to the success in renewables dominating the combined fossil fuels in electricity mix in the EU has been directly due to the immediate results of the European Green Deal policies, and what part of it follows from a general economic advantage of renewables, some discussion in this regard is certainly needed. One of immediate effects of the 2018 recast Renewable Energy Directive (2018/2001/EU) that is considered to be a part of the current European Green Deal package is certainly related to increase of funding in renewables related research and development on many levels affecting the efficiencies of the renewable energy generation. E.g. for the solar power, multiple industrial research projects funded by the EU resolved to significantly decreasing costs of fabrication of, on the other hand, increasingly efficient solar cell devices, driving down the costs per Watt of electric energy generated. PV related research results include also plasmonic enhancements of solar cells (c.f. Jacak et al. 2018-2020) which allow for cost-efficient increases of energy generated from solar cell devices by surface nano-modifications. Also improvements in smart grids and energy production decentralization towards enabling the prosumer model indirectly extend potentials and economic advantages of renewable energy sources and is most certainly driven by relevant Green Deal policies in the EU, such as to enable prosumers to sell their produced energy to the grid (along with following investments and technological developments in renewables in general). Furthermore it should be emphasized that one of major impact factors that makes renewable energy sources more cost efficient than traditional fossil fuels in electricity generation comes from the Emission Trading System which has been imposed upon a climate-related political agreement in the EU and ever since introduces kind of an artificial (yet justified by climate goals) burden for the fossil fuels, further assisted by economic speculation in terms of emissions market trading. Other political factors contributing to economic advantage of renewables in the EU was a German anti-nuclear policy imposed in 2011 after the Fukushima incident, resulting with a complete phasing down of nuclear power in this country, strongly driving renewables growth in the EU. Due to a high level of climate awareness already in 2011, the new energy sector direction in Germany has been shifted towards increasing share of renewables (along with controversial increasing of natural gas supply dependence from Russia in Nord Stream 1 & 2) rather than upscaling polluting electricity generation from coal (which also has a significant share in Germany, but started losing ground to renewables because of the ETS economic pression, which is however directly rooted in the climate policy). On a level of the European Union these policies are now encapsulated in the European Green Deal package, with new climate-neutrality initiatives and ambitious developments that will be surfacing in upcoming years.

Although the funding of the European Green Deal is currently programmed at €1 trillion (as mentioned the plan involves mobilizing of at least €1 trillion of investments over the course of 10 years in the EU), such value nominally is rather corresponding to an estimated amount of the necessary annual spending in the EU required to reach the net zero emissions target in 2050 (hence it is by one order smaller from what is actually needed). Certainly it is hence an initial investment plan, that will require to be further extended and most importantly trigger increasingly growing private investment, that in total should be at least 10 times greater in scale of a corresponding time frame of ten years (and by a factor of ca. 30 when we consider almost three decades left to 2050). Already in September 2020 the European Commission (along the lines of the communication entitled Stepping up Europe's 2030 climate ambition - Investing in a climate-neutral future for the benefit of our people - Impact assessment, COM(2020) 562, September 2020) has predicted that meeting the 2030 climate objective would necessitate additional investments of almost €360 billion in the EU alone each year. This increases the relevant investments scale for the EU from an average of €683 billion per year in the previous decade to about €1 trillion per year. The transportation sector accounts for ca. a third of the required investment, and is by far the greatest component due to a massive combustion engines vehicles replacement necessity that would facilitate reaching the climate neutrality goal. However major magnitude upon this investment is on a consumer level, i.e. depending on average EU citizens transiting from buying combustion engine cars to electric vehicles.

This transition rate will scale increasingly in upcoming decade (even with a discussed ban on combustion engines cars production) but will be closely tied to investments needed for widespread electric cars charging infrastructure (quite differentiated in the EU, and in need to be specifically enhanced in the Eastern European member states). Apart from the transportation sector, also the focus is also set on tripling home heating investments which falls under a scope of the buildings modernization EU policy, while other important components of the EU energy policies (minor in terms of investments magnitudes) such as electricity grids and power plants must still be increased by at least a factor of two. These estimates were produced by the European Commission only in regard to reaching more modest 2030 targets, while the 2050 target for a full carbon neutrality will certainly exceed these costs even further, with a remark that large part of these investments will be in a transportation sector with consumers' major shift to its electrification.

The scale of the global energy investment magnitudes for achieving net zero emissions by 2050 is of course correspondingly larger. According to the International Energy Agency, it currently amounts by rough estimates to well over \$2 trillion per year, or 2.5% of the world GDP (Net Zero by 2050, A Roadmap for the Global Energy Sector, Flagship report, International Energy Agency, May 2021). This is quite an optimistic estimation that only considers immediate future of up to few years. After this short term time scale in order to achieve net zero CO_2 emissions by 2050, according to the mentioned model of the IEA, the investment will have to climb to \$5 trillion globally per year (or ca. 4.5 percent of GDP) by 2030 and stay at least at this level, until 2050. Significant amount of this investment will also need to go towards electricity generation and infrastructure in order to electrify new economic areas and make the electric grid more capable for dealing with much higher volumes and variability of renewable energy, especially concerning the widescale electrification of the transport. The International Renewable Energy Agency along the lines of the World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency, June 2021, projects similar estimates in terms of the required expenditures to be made in the current decade, resulting in annual spending of \$5.7 trillion until 2030, with an expected minor decrease in a period between 2030 and 2050. Finally, according to the Bloomberg New Energy Finance (New Energy Outlook NEO, July 2021), global investment needs will range between \$3.1 trillion and \$5.8 trillion each year until 2050. According to these estimations, the goal of achieving climate neutrality globally by 2050 will also require ca. 2% of GDP in increasing of additional investments in energy and transportation infrastructure from the current levels (i.e. close to a figure of 2.5% estimated by the IEA). Because of the size and scope of the required investments, they will have major macroeconomic effects, both in a global scale, as well as in the EU. These policies will hence be strongly conditioned by the macroeconomic situation in the world. In this regard it is certainly crucial to point at major risks glooming on the horizon. One of such risks is a currently developing global crisis triggered by the 2022 invasion of Russia on Ukraine. The western economic sanctions (significantly increased by the EU on 27th February 2022) may be a major factor in necessity to rescale the climate policy, in view of dire challenges the world now faces with Russian aggression and risks for the conflict to upscale, along with strong global economic impacts, that have only begun.

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B-03. PV Manufacturing; Reliability

Needs, Challenges and Approaches for new Service Life Estimation Models for PV Modules- Results from IEA-PVPS-Task 13 Subtask 1.4

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Abstract

The economic success of photovoltaic (PV) power plants depends crucially on the lifetime energy yield. The degradation effect and the total lifetime directly influence the produced electricity and therefore the cash flow. In most cases, lifetimes and degradation rates, which are used for the estimation of plant behaviour, are nowadays still not system specific, but based instead on average values of evaluations of older systems or data sheets. So, these values unfortunately have no direct correlation with the specific components of the respective PV system. Also, the mathematical models used for calculated power output typically expect linear degradation rates which are not found in real degradation processes found in the field.

Activity 1.4 of the IEA PVPS Task 13 developed an overview on service life prediction and degradation modelling of PV modules since they are the major component of PV systems causing degradation effects and for other components no comparable scientific data is available.

The presented description is a reproduction of the Executive Summary of the report [1].

Keywords: PV Module, Reliability, Degradation, Modelling

1. Introduction

The economic success and environmental impact of photovoltaic (PV) power plants depends crucially on the degradation and service life of the PV modules and other components of the PV power plants. The behaviour of PV modules is especially relevant since they typically show gradual degradation effects over time. The useful service lifetime and degradation of PV modules directly influences the lifetime yield of electricity, and therefore, the levelized cost of the electricity (LCOE) produced. Degradation and service life are influenced not only by the materials used and the quality of module manufacturing, but also by local environmental effects that dictate the exposure conditions of the PV modules. Therefore, the lifetime and degradation of PV modules cannot be determined easily and are not valid for all locations and applications. Since both are dependent on local and operational conditions, the prediction of service lifetime from PV module degradation rates must be taken into consideration all of these factors and incorporate them into mathematical models.

The presented description is a reproduction of the Executive Summary of the report [1]. The complete report is available online https://iea-pvps.org/publications/

2. Structure of the report

This report introduces the influencing factors for service life and degradation of PV modules and components as well as the modelling of degradation effects and service life prediction. It describes relevant stresses and load effects in section 3 and different modelling approaches, as well as models which have shown to fulfill the requirements of PV stakeholders in section 4. The descriptions are written in a way to address the needs of readers from all stakeholder groups, so on one hand people with no background in mathematical modelling who are interested in the influencing factors, potential of service life prediction, and interpretation of given data, as well as experts in reliability and degradation modelling. The chapters therefore briefly describe the approaches and background as well as examples

and list relevant literature for further reading.

Since the content of the report would exceed the possibilities of such a conference paper, only the executive summary is presented in the following. The readers are encouraged to download the full report [1] which is available on the IEA PVPS Task 13 website https://iea-pvps.org.

3. Executive summary

The economic success of photovoltaic (PV) power plants depends crucially on their lifetime energy yield. Degradation effects and the total lifetime directly influence the produced electricity and therefore the cash flow, which also impacts the levelized costs of energy (LCOE) and therefore the profitability of the power plant. In most cases, the lifetimes and degradation rates that are used to estimate the system performance are not system-specific, but are based on average values from the evaluations of older systems or data sheets. So, these values unfortunately have no direct correlation with the specific components of the specific PV system, nor the operational and climatic conditions at the specific location. Also, the mathematical models used for calculating the expected power output typically expect linear degradation rates which are not in line with real degradation processes found in the field, which are typically non-linear.

This report gives an overview on empirical degradation modelling and service life prediction of PV modules since they are the major components of PV systems that are subject to the effects of degradation. For other components, no comparable scientific data is available. The structure of the document addresses different stakeholders with different backgrounds. Chapter 1 begins with a short introduction including a condensed overview of the state of the art.

Chapter 2 follows with the definition of relevant terms and definitions. Since especially in discussions on lifetime and degradation different terms are not used coherently in industry or science, the authors try to improve the situation with this dedicated glossary. In addition, the extremely relevant term "end-of-life" is discussed with different definitions, depending on the point of view and perspective of the user and the typical factors impacting the PV module or PV system. For this "end-of-life" term, no definition which is generally applicable in all situations can be given. Since the definition is crucial for the calculated service life, yield, and all related parameters, through to LCOE it is important to be aware of this when evaluating power plants and PV investments.

Climatic factors play a major role in degradation and are by nature location specific. It is precondition for the creation of meaningful service life prediction or degradation data to know about the relevant (climatic) stressors. Therefore Chapter 3 introduces the different relevant climatic stressors as well as classification schemes and methodologies to handle and analyse them. The chapter also describes differences and relations of the so-called macroclimatic stressors, describing the climatic conditions in the ambience of the modules, and the situation at material level, the so called micro-climatic stressors. The latter describes the relevant parameters for degradation processes and so also the mathematical models addressing module degradation and service life prediction. The ambient macro-climatic conditions at specific locations can be estimated using data for the climatic regions or adapted climatic maps and so be classified using climatic classification schemes which exist also specified for PV purpose like the Köppen-Geiger PV scheme. For the determination of microclimatic loads - which are typically input parameters for degradation models, further calculations are necessary. The report presents possible ways to determine the necessary data for the most important micro-climatic parameters which are temperature and humidity. This data is also very important for the definition of accelerated tests, which can deliver module specific parameters for the service life and degradation prediction. Chapter 3 also describes basic accelerated ageing tests, as described in the respective IEC standards, and how they can support degradation and service life prediction and modelling as well as their limitations.

Chapter 4 addresses general degradation and service-life modelling approaches including related issues. It starts in section 4.1 with general issues of empirical modelling one has to be aware of when working on mathematical modelling solutions for service life and degradation prediction and interpreting results. There are very different approaches for empirical modelling of the lifetime performance prediction and service life of products such as PV modules empirical statistical modelling, and empirical physical modelling. Physical empirical models are those that utilize analytic or numerical forms to represent the fundamental physics

and chemistry of the phenomena. Statistical models, often referred to as data driven models, use mathematical forms which are able to fit the (measured) data without direct relation to physical or chemical processes. Both approaches use empirical (measured) data to determinate parameters which can be used for predicting future behaviour.

Section 4.2 introduces on one hand models for specific degradation modes or phenomena of modules (e.g., backsheet

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or cell cracking or electrochemical corrosion). On the other hand, modelling approaches for degradation effects of components and materials are presented. A special focus is here on degradation of polymeric materials since these materials are known to be sensitive to degradation effects causes by typical climatic stressors like high temperature, humidity and UV radiation. The modelling approaches using predictive models and inferential mechanistic models are presented using polyethylene terephtalate (PET) degradation as catchable example. It is shown that different modelling approaches are necessary to describe all degradation effects. Weak points of modules can be identified, and focussed optimization of products can be supported.

Performance degradation models are addressed in Section 4.3 which are the core models for the prediction of degradation of modules over time for specific types and locations. Combined with defined end-of-life conditions, these models can be used for service life prediction. Different approaches which have been specifically developed for PV modules are presented. Starting with an approach focusing on physical and chemical processes and the specific application. An approach to develop performance loss rate (PLR) models following the statistical methodology is presented as well including the processes to determine the relevant parameters from field data.

The modelling approaches are presented including the methodological approach to the problem the used input data, and parameters related to specific module types or local climatic conditions, down to calculations of degradation rates over time or remaining useful lifetime

(RUL) or total expected lifetime.

The latest scientific work shows that service lifetime and degradation models for PV modules are of specific use if they combine different modelling approaches and include know-how and modelling parameters of the most relevant degradation effects. Such models can differentiate between the behaviour of different module types and to include the situation at different service locations. For some modules, it is also necessary to use multi-step modelling approaches to enable meaningful results.

Advanced approaches of data analysis and modelling also enable the determination of degradation signatures which can be related to specific degradation effects. This approach is expected to be very helpful in future work to identify failures based on operational data.

Since uncertainties of input parameters can have significant impact on the results but are often not totally avoidable, these topics are addressed in Chapter 4.3.

4. Acknowledgments

This paper is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) under contract no. 0324304A and 0324304B.

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B-04. Recycling and Sustainable Material Usage;

Towards Multi-TW Scale Manufacturing of PV Technologies: Challenges Related to Material Consumption

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Abstract

Key roadmaps suggest that for photovoltaics (PV) to play a significant role in avoiding climate change, a multi-TW market (~ 1-3 TW p.a.) needs to be established during 2030-2050. With a potential tenfold increase in the annual manufacturing scale, the consumption and availability of key materials such as silver, indium and bismuth will raise serious concerns for the PV industry. Currently, the mainstream solar cell technology, passivated emitter and rear cell (PERC) has a silver consumption level of 15.4 mg/W, which would require more than 160% of the global silver supply to support a 3 TW manufacturing capacity. Even with a projected 50% reduction in silver usage per cell in the next decade, a multi-TW market will still consume the majority of global silver supply. The potential transition from PERC to next-generation screen-printed tunnel oxide passivated contact (TOPCon) cell or silicon heterojunction (SHJ) solar cells represents a big step backwards for sustainable PV manufacturing due to limited efficiency gain and almost twice higher silver consumption. A transition to SHJ could also introduce new material challenges like indium and bismuth. Indium-based transparent conductive oxide (TCO) cannot be used in large-scale manufacture of any cell technology even for 30% tandem solar cells, indicating the need for indium-free TCO for both SHJ and tandem solar cells. The use of bismuth-based low-temperature interconnection technologies will also be limited to niche applications.

Keywords: photovoltaics (PV), terawatt scale, material consumption, screen print, sustainability

1. Introduction

To fulfill the requirement of The Paris Agreement, to limit the global warming to well below 2 °C or even 1.5 °C compared to pre-industrial levels (United Nations Climate Change, 2015), greenhouse gas emissions must be significantly reduced from now on, especially those from the energy generation sector, which is contributing more than 25% of total emissions (United States Environmental Protection Agency, 2021). With rapid developments in renewable energy technologies, several renewable energy sources such as solar photovoltaics (PV), geothermal, and wind have already achieved comparable or even lower costs than the conventional fossil fuels (LAZARD, 2019), providing not only technologically feasible but also economically viable alternatives. However, the large-scale deployment of renewable energy sources implies a significant increase in demand for raw materials such as copper, zinc, and silver, raising the risk of material shortage, increases in costs, and delayed transitions towards renewable energy sources. A study by the International Energy Agency (IEA) clearly highlights such a risk and concludes that today's mineral supply and investment plans fall short of what is needed to transform the energy sector from the traditional fossil fuels to green energy (International Energy Agency, 2020). For other more abundant materials such as steel, aluminum and copper, due to a high consumption level on the system level, the requirements for TW scale deployment of PV are massive. This raises concerns of the availability of these materials and also negative social and environmental impacts from the minerals production (Hund et al., 2020).

PV technologies have great potential to play a central role in the future clean energy system due to their pronounced advantages in accessing abundances of solar energy, predictable energy output based on the weather

forecast, low land consumption, easy installation and maintenance, and low costs. Historically, the PV industry has already exhibited its capability of fast growth, where the annual production capacity rapidly increased from 16 GW to more than 130 GW during the past decade (ITRPV, 2021). Providing such a growth rate can be sustained, the PV industry is well on-track towards a terawatt manufacturing scale by 2030. In addition, key roadmaps also identify that a multi-TW market (~ 1-3 TW p.a.) needs to be established for the PV industry by 2040 to significantly fight against climate change and to avoid a major downturn in newly installed capacity due to the replacement of end-of-life modules (Haegel et al., 2019; ITRPV, 2020; Shell, 2018; Verlinden, 2020). However, such a rapid and continued growth will significantly increase the consumption of rare elements such as silver, indium, and bismuth, leading to continuously increased concerns associated with sustainable PV manufacturing at the terawatt scale. As a result, the PV industry must start to evaluate PV technologies in respect to their consumption of key materials, rather than purely focusing on efficiency and cost, to ensure the large-scale deployment of those emerging new technologies is feasible. In this mindset, we will primarily address PV material constraints of immediate concern such as silver consumption in screen-printed contacts, indium consumption in transparent conductive oxide layers (TCO), and bismuth consumption in low-temperature solders in both current and future cell technologies, with a secondary focus on efficiency increases to improve systems-level material consumption for all materials including abundant materials such as silicon, copper, aluminium and steel.

2. Silver Consumption in Silicon Solar Cells

The most pressing concern for TW scale PV deployment comes from silver(Verlinden, 2020; Zhang et al., 2021), as silver is currently used in the metallization of essentially all industrial silicon solar cell technologies, including aluminum back-surface-field (Al-BSF), passivated emitter and rear cell (PERC), tunnelling-oxide passivated contact (TOPCon) and silicon heterojunction (SHJ) solar cells. Even for the futuristic two-terminal (2T) tandem solar cells, screen printing of low-temperature silver pastes still offers a promising approach for metallization in mass production. In 2020, the PV industry already consumed 2800 tonnes of silver, corresponding to about 11% of the global silver supply (The Silver Institute, 2021a), with an annual production capacity of ~ 130 GW as shown in **Fig. 1 (left)**. With this consumption level, as the industry is heading towards a terawatt scale, PV will likely become the dominant consumer in the global silver supply chain, and the existing supply level might fall far short of meeting the demand of PV industry at a terawatt level. Given the global annual supply of 29,000 tons of silver in 2019 (The Silver Institute, 2021a), to allow a 3 TW manufacturing scale using no more than 50% of the global silver supply, silver consumption needs to be reduced to less than 5 mg/W regardless of the cell structure.



Fig. 1: (left) silver consumption by industries in 2019 (The Silver Institute, 2021a), (right) projected annual silver demand from the auto manufacturing industry (The Silver Institute, 2021b).

On the other hand, the demand for silver from other industries such as transportation and electronics is also expected to significantly increase over the next decade. As a key component in the clean energy transition, electric vehicles (EVs)/hybrid electric vehicles (HEVs) require 1-1.5 times more silver than conventional internal combustion engine (ICE) vehicles (The Silver Institute, 2021b). **Fig. 1** (**right**) shows a potential 3.5 times increase in the silver demand from the auto manufacturing industry by 2040. There is no doubt that the increased demand from other industries will apply additional pressure to the global silver supply, which will likely reduce the amount of silver that can be used in the PV industry. Given the low selling price and high silver consumption of solar

cells, the PV industry will have little tolerance to any silver price fluctuations and cannot afford paying more for silver in order to secure more silver supply in the event of supply shortage. As a result, from the long-term perspective, a target well below 5 mg/W should also be considered for all solar cell technologies in the future.

The silver consumption per cell has been substantially reduced from more than 400 mg per cell in 2010 to less than 100 mg per cell in 2020 owing to the largely reduced finger width and the transition from the traditional 3-busbars to a multi-busbar (>9 busbars) configuration. The increased number of busbars largely reduces the silver consumption in busbar regions and finger series resistance, which then allows further reductions in finger silver usage without increasing power losses from finger series resistance. However, there is a clear trend that the silver reduction is decelerating as shown in **Fig. 2**. Historically, it took less than 3 years to half the silver consumption per cell from 400 mg in 2010, and less than 5 years to reach a level of 100 mg per cell. As for today, reducing the silver usage from 100 mg per cell to 50 mg per cell will likely take more than 10 years in the future. That raises the question that if the silver reduction will be fast enough in the coming decade to maintain a reasonable total silver consumption level for the PV industry, providing a multi-TW manufacturing scale has been projected by many studies (e.g., 3 TW by 2030 from Verlinden (2020), 4.5 TW by 2050 from ITRPV for the broad electrification scenario (ITRPV, 2021)).



Fig. 2: Historical and projected silver consumption per cell for Al-BSF/PERC, TOPCon and SHJ solar cells (ITRPV, 2021) in G1 wafer format (158.75 × 158.75 mm²).

The transition to different solar cell technologies can also impact the silver consumption level. Historically, the shift from traditional Al-BSF to PERC structure provided the scope of a 10-20% reduction in silver usage due to the increased efficiency. However, the same cannot be said for the potential transition of the industry from PERC towards next-generation TOPCon or SHJ technologies. The limited efficiency gain of TOPCon and SHJ does not justify the almost twice higher silver usage due to the need of silver fingers, busbars and soldering tabs on both sides of the devices. The high silver consumption in TOPCon and SHJ will not only result in significantly increased manufacturing costs, but also impose a much stricter constraint on the sustainable manufacturing capacity of those technologies for a given percentage of the global silver supply.

	2020			2030 Expected (ITRPV)		
	(mg/cell)	(mg/W)	% of global supply for 3 TW	(mg/cell)	(mg/W)	% of global supply for 3 TW
PERC	96	15.4 (η=22.8%)	159%	50	8.1 (ŋ=23.9%)	84%
TOPCon	163	25.6 (η=23.2%)	300%	90	15.0 (η=24.5%)	155%
SHJ	150-240	25-41 (ŋ=23.1%)	260-430%	90	14.0 (η=25.0%)	145%

Tab. 1: Silver consumption of different solar cell technologies in 2020 and expected values in 2030 (ITRPV, 2021).

Nevertheless, **Tab. 1** shows values of silver consumption of different cell technologies in 2020 and 2030 according to ITRPV's analysis. In the coming decade, the mg/W usage of silver in all major industrial solar cell technologies is expected to be reduced by 40-50% due to improvements in efficiencies and reductions in silver laydown per cell. However, by 2030, the projected silver consumption is still well above 5 mg/W for all technologies. As a

result, an annual production capacity of 3 TW will consume more than 80%, 155%, 145% of the global silver supply for PERC, TOPCon and SHJ solar cells, respectively. This suggests that the projected reduction in silver consumption of industrial solar cells will likely be insufficient to allow a 3 TW manufacturing scale in the coming decade, and it also rules out the option of having n-type technologies such as TOPCon and SHJ using screen-printed silver contacts as the mainstream technologies in a TW market.



Fig. 3: (left) Allowable finger cross-sectional area as a function of finger silver usage, (right) relative finger resistive losses as a function of finger silver usage. All values are calculated for solar cells on G1 wafers (158.75 × 158.75 mm²), with the assumed efficiency of 23.9% for PERC, 24.5% for TOPCon and 25.0% for SHJ based on 2031 predictions of stabilized efficiency in the 2021 ITRPV (ITRPV, 2021). Filled symbols provide values for current industrial cells, opened symbols represent a total silver consumption of 5 mg/W with silver busbars and tabs. Half-filled symbols denote the finger silver usage of 5 mg/W or 2 mg/W.

Given that the silver consumption in finger regions accounts for more than 50% of the total usage in PERC, and more than 70% for TOPCon and SHJ, further reductions in silver consumption level requires a substantial reduction in finger silver usage. For PERC solar cells, assuming a finger spacing of 1.3 mm, a finger silver consumption of 5 mg/W requires the finger cross-sectional area to be reduced to no more than 300 μ m² as shown in **Fig. 3 (left) and Tab. 2**, which is not too far away from current value of 400-500 μ m² in industrial solar cells. However, for TOPCon and SHJ solar cells, due to the need of silver fingers on both sides, 5 mg/W of finger silver usage can only tolerate a finger cross-sectional area of ~150 μ m², which will likely point towards a target finger width of no more than 20 μ m. Providing that the finger width of ~ 20 μ m has already been successfully demonstrated in the laboratory, such a finger cross-sectional area can be considered as realistic and feasible in the near future. However, the impact of largely reduced finger cross-sectional area on the reliability and printability of such fingers needs to be carefully evaluated in the mass production environment.

		PERC	TOPCon	SHJ
Current Industrial Cell	Finger CA (µm ²)	450	450	450
	Ploss;finger Rs (%rel)	0.21	0.38	0.6
5 mg/W fingers only	Finger CA (µm ²)	304	170	150
	Ploss;finger Rs (%rel)	0.36	1.34	2.48
5 mg/W with 9BB and soldering tabs	Finger CA (µm ²)	59	6.8	9.3
	Ploss;finger Rs (%rel)	1.95	33.6	41.3
2 mg/W fingers only	Finger CA (µm ²)	122	68	60
	Ploss;finger Rs (%rel)	0.91	3.36	6.20

Tab. 2: Allowable finger cross-sectional area (CA) and relative finger resistive losses of different solar cell technologies.

On the other hand, silver is also needed in busbar and soldering tab regions for interconnection purposes. With the existing 9BB configuration in typical industrial solar cells, more than 4 mg/W and 4.7 mg/W of silver is used in those regions for PERC and TOPCon/SHJ solar cells, respectively. That means, with a target of total silver consumption of 5 mg/W, there is only 1 mg/W of silver which can be used in fingers for PERC, and less than 0.3 mg/W for TOPCon and SHJ solar cells. As a result, the maximum allowable finger cross-sectional area is

dramatically reduced to less than 60 μ m² for PERC and an unrealistic value of less than 10 μ m² for TOPCon and SHJ. Therefore, eliminating the silver usage in busbars and tabs regions and the transition towards busbar-less interconnection schemes will be essential for all cell technologies to achieve a silver consumption level of 5 mg/W, especially for TOPCon and SHJ solar cells. Even with a busbar-less or silver-free-busbar configuration, the maximum allowable finger cross-sectional area for a total silver consumption of 2 mg/W will still be very challenging, suggesting that more innovations will be required to fundamentally change the way fingers are printed in order to achieve the 2 mg/W target.

$$Ploss_{finger\ Rs;rel} = \frac{J_{mp}}{V_{mp}} \cdot \frac{L_c^2 \cdot S_f \cdot \rho_m}{3 \cdot W_f \cdot t_f} = \frac{J_{mp}}{V_{mp}} \cdot \frac{W_{cell}^4 \cdot \rho_f \cdot \rho_m}{12 \cdot N_{BB}^2 \cdot M_{Ag}}$$
(eq. 1)

In addition to the constraints imposed by the physical dimension of fingers, potential increases in the finger resistive losses as the finger silver usage reduced also need to be carefully evaluated. The relative finger resistive losses (Ploss_{finger Rs;rel}) are traditionally calculated based on half busbar spacing (L_c), finger spacing (S_f), finger resistivity (ρ_m), finger width (W_f) and finger height (t_f) as shown in Eq. 1. By rearranging this equation, a direct correlation between relative finger resistive losses, silver usage in fingers (M_{Ag}), the number of busbars (N_{BB}), finger resistivity (ρ_m), paste mass density (ρ_f) and the width of cell (W_{cell}) can be subsequently established. As such, reducing the finger silver usage will inevitably increase the finger Rs losses regardless of the finger spacing or the exact finger geometry. As shown in Fig. 3 (right) and Tab. 2, with a finger silver consumption of 5 mg/W (2 mg/W), the finger Rs losses will be increased by a factor of 1.7(4.3) for PERC, 3.5(8.8) for TOPCon, and 4(10.3) for SHJ, respectively. Finger Rs losses will be substantially higher if silver is also used in busbar and tab regions. With an existing 9BB configuration, a total silver usage of 5 mg/W will lead to a finger Rs loss of 1.95% rel for PERC, 33.6% rel for TOPCon, and 41.3% rel for SHJ, which again highlight the necessity of transitions towards a busbar-less configuration for all solar cell technologies in the future. Another striking feature of equation.1 is the inverse quadratic dependence of finger Rs losses on the number of busbars or interconnection wires. As a result, increasing the number of busbars/wires will provide an effective pathway to reduce the finger Rs losses, which should be considered as a necessary step to take in conjunction with reducing finger silver usage to avoid excessive increases in finger Rs losses.

The futuristic two-terminal (2T) tandem solar cells present a unique opportunity to not only achieve ultra-high efficiencies but also reduce the silver consumption significantly. The mg/W silver usage of tandem is naturally reduced by around 25% compared to existing industrial solar cells if an efficiency of 30% can be achieved on tandem. Another key feature of 2T tandem devices is the low current but high voltage output, which reduce the ratio of J_{mp} to V_{mp} by a factor of 6 (Sahli et al., 2018; Xu et al., 2020), leading to largely reduced resistive losses including finger series resistance and lateral resistance compared to PERC, TOPCon and SHJ solar cells. The choice of finger spacing in solar cells is essentially a trade-off between resistive losses and optical shading losses. With much lower resistive losses in 2T tandem solar cells, a much larger finger spacing can be used, resulting in a massive reduction in the finger silver usage. Based on our estimation, a total silver consumption of less than 5 mg/W could readily be achieved in bifacial 2T tandems with existing screen-printing technology and an industrial standard 9BB configuration. With further reductions in finger width and possible transitions towards a busbarless configuration, 2T tandems are well on-track towards the long-term target of 2 mg/W silver usage.

In addition to innovations in screen-printing technology, copper (Cu) plating should be seriously considered as an alternative for TW scale PV manufacture. Since the copper required for plating is at a very small quantity, transitions towards plating will have negligible impact on the overall copper consumption on the system level, which will not introduce additional concerns related to copper consumption for the PV industry. Copper plating has been successfully adapted by a number of companies over the years, such as BP solar (Bmton et al., 2003; Wenham et al., 1994), Suntech (Shi et al., 2009; Wang et al., 2012) and Sunpower (Mulligan et al., 2003; Neuhaus and Münzer, 2007). Recently, a new record efficiency of 25.54% has been achieved by SunDrive and Maxwell on plated SHJ solar cells (PV-magazine, 2021). This new record efficiency marks an important milestone that shows copper plating can provide a viable path to high efficiencies not only in a lab environmental but also on industrial cells. However, several potential challenges still need to be evaluated and overcome for copper plating, such as the need of a diffusion barrier to avoid Cu penetration into the cell, potential issues with the adhesion and long-term reliability, and also the management of liquid metallic waste (Lennon et al., 2019).

3. Indium Consumption in Silicon Solar Cells

Indium is another material concern for the PV industry, which is commonly used as the form of indium tin oxide (ITO) in transparent conductive layers (TCOs) in SHJ and Perovskite solar cells or interlayers between top and bottom cells in tandem devices. It should be noted that TCOs are not needed in Al-BSF, PERC and TOPCon solar cells, hence imposing no constraints to the manufacturing capacity of those solar cell technologies. Indium is an extremely rare element, which has a global reserve 10 times lower than that of silver, and a 30 times lower annual global supply level (United States Geological Survey, 2020a). Indium is mainly produced as the by-product of zinc during extraction and processing. That means unless there is a significant increase in the demand and production of zinc, producing more indium will be not only difficult but also expensive. The secondary production from recycling (~1000 tonnes per year) also plays a critical role in the supply chain of indium, which accounts for more than half of the total global supply in 2019. However, the concern is that indium used in PV modules will be effectively locked up for 25-30 years rather than be recycled and reused every 3 years from touch screens (Islam et al., 2020), which subsequently will have a negative impact on the overall indium supply if a significant amount of indium is consumed by the PV industry.



Fig. 4: Indium consumption with different thickness of ITO layers.

Currently, typical industrial SHJ solar cells use around 85 mg of ITO per cell, corresponding to an indium consumption level of 7.5-11 mg/W. With this consumption level, the planned capacity of SHJ solar cells in 2021 (40-50 GW) could already consume 30-60% of the annual global supply of indium. To achieve a 3 TW of SHJ production using no more than 20% of the total supply, the indium consumption in SHJ solar cells needs to be reduced to less than 0.2 mg/W, which then will only tolerate 3 nm of ITO per side being used instead of 80-100 nm in existing SHJ solar cells as shown in Fig. 4. The use of such thin layers is clearly unrealistic from either the performance or the production perspective. As a result, ITO can only be used in a niche application, which then will significantly limit the sustainable manufacturing capacity of solar cell technologies that requires ITO. Although the stacked layer configuration consisting of ITO and other indium-free dielectric layers can provide a promising pathway to significantly reduce the indium consumption (Boccard et al., 2019; Yu et al., 2018; Zhang et al., 2013), the use of 3 nm of ITO in such configurations would still be unrealistic. To enable sustainable manufacturing of SHJ solar cells and futuristic tandem devices at the TW scale, the use of indium-free TCO layers must be explored to completely overcome limitations imposed by the indium supply. Aluminum-doped zinc oxide (AZO), as one of the very few potential candidates, has attracted significant attention due to its low cost and abundant nature in material and capability of achieving comparable efficiencies to ITO-based SHJ solar cells. However, a significant amount of effort still needs to be put into battle with the relatively poor conductivity and long-term stability of AZO layers.

4. Bismuth Consumption in Silicon Solar Cells

Bismuth (Bi) is well known as a non-toxic replacement for lead in many applications such as pharmaceuticals, pigments and cosmetics. In the PV industry, the lead-free nature of Bi-based solders presents a more environmentally friendly option, which has long been criticized for the use of ribbon coating and soldering pastes containing lead, against the industry's credentials of providing clean and green energy. Another key advantage of using Bi-based solder is the low soldering temperature, typically below 150 °C, compared to the soldering

temperature above 200 °C needed for the conventional Sn/Pb solders (Faes et al., 2014). The low soldering temperature could help avoid cell breakage, cell bowing, and the formation of microcracks by reducing the thermal-induced stress caused by the mismatch of the thermal expansion coefficients of Cu ribbon wires and Si substrate, especially in solar cells fabricated on thinner and larger silicon wafers, a trend that is likely to continue in the future. In addition, low-temperature soldering is particularly beneficial for SHJ solar cells, of which the surface passivation quality of amorphous silicon layers could be jeopardized by any high-temperature thermal processing. Bi-based low-temperature interconnection methods such MBB in conjunction with bismuth coating or the busbar-less SmartWire technology will potentially become the standard interconnection technology for SHJ modules. The use of low-temperature alloys will likely also be important for future tandem solar cell technologies involving perovskites, again with temperature restrictions.



Fig. 5: Allowable annual production capacity using bismuth-based interconnection technologies as a function of the number of wires per side of the solar cell.

Assuming 18 wires per side with a coating thickness of 3 µm and a wire diameter of 300 µm, typical SHJ solar cells with 25% efficiency will have a bismuth consumption level of around 13 mg/W. This architecture is equivalent to using more than 60% of the global Bi supply in 2019 to produce 1 TW of solar cells. When limited to using 20% of global supply, only 325 GW of solar panels can be produced per year. For a 3 TW manufacturing capacity, the bismuth consumption needs be reduced to 1.4 mg/W assuming 20% of the global bismuth supply is available to use for the PV industry, which then will only allow no more than 2 wires per side for SHJ solar cells as shown in **Fig. 5**. Although reducing the number of wires provides one of the most efficient ways to reduce the bismuth consumption level, it will also significantly increase the resistive losses along fingers and along wires, not only leading to substantial power losses, but also making the silver reduction in fingers even more challenging. For instance, finger resistance losses will be increased by a factor of more than 20 compared to current industrial 9BB configuration if only 2 wires can be used per side. This will likely not be feasible for any single-junction technology, including PERC, TOPCon and SHJ solar cells. However, 2T tandem devices with a much lower resistive loss could potentially have better tolerance to the reduced number of wires, where it may be feasible.

5. Beyond the Scope of Supply and Availability

In addition to those scarce metals, materials like steel, aluminum and copper are also essential to solar PV. Steel is mostly used in the balance of system (BoS) components such as racking systems and transformers, and aluminum is commonly used in module frames. On the other hand, copper has wide applications from the cell to the system level including Cu tabbing ribbons for the interconnection between cells, modules, array and field cables, and transformer windings. Although the demand of these materials is much higher than scarce metals, thanks to the huge global supply chain and the well-established recycling industry, these more abundant materials are facing no significant supply issues with the current usage lower than the target usage for the upcoming TW manufacturing scale as shown in **Tab. 3**.

Tab. 3: Current material usage, target usage for 3 TW production scale, and material demand of steel, aluminum and copper.

	Current Usage (g/W)	Target Usage (g/w)	2020 Global Annual supply (Mt)	Total Demand for 3 TW annual production (Mt)
Steel	30-45	120	1800	90-135
Aluminum	9	8.6	130	27
Copper	2.8	1.8	24.6	8.4

However, the high consumption levels of those materials and substantially increased demand from the primary production will raise serious concerns for greenhouse gas emissions, negative environmental and social impacts from mineral production. A recent study by The World Bank has identified potential global warming issues with aluminum, claiming it will be responsible for more than 90% of the greenhouse gas emissions from aluminum production in next decade (Hund et al., 2020). IEA also highlights that failure to manage the environmental and social impacts from material production will slow down clean energy transitions (International Energy Agency, 2020). As such, the future growth of the PV industry needs to be not only sustainable but also responsible. On one hand, the reliance on materials from primary production must be significantly reduced by lowering the overall material consumption even there are no immediate supply concerns. The prioritized consumption of materials from secondary production is less emissions intensive. On the other hand, new PV systems need to be designed and produced in a way that key materials can be easily reused or recycled in the future (Ardente et al., 2019; Norgren et al., 2020).

6. Conclusion

In summary, as the PV industry heads towards TW scale manufacturing, we need to shift our focus from efficiency and cost to understanding the limitations of material consumption and exploring options of reducing the usage of key materials. Silver is currently one of the biggest concerns for the PV industry, even for PERC. The high silver consumption in TOPCon and SHJ solar cells will impose significant challenges for them to become the mainstream technology in a future TW market. To allow a 3 TW of annual production capacity, we need to limit the silver usage to less than 5 mg/W or more preferably 2 mg/W regardless of the cell structure. As such, in addition to the natural reduction in finger width and possible transition towards a busbar-less configuration, more innovations are required for printing and we also need to seriously consider the Cu plating as an alternative, especially for TOPCon and SHJ solar cells. For indium, ITO is a no go for SHJ or even 30% tandem in large scale manufacturing. We need Indium-free TCO replacement or to fundamentally eliminate the use of TCO in those structures. Bismuth imposes another constraint to the sustainable manufacturing capacity of SHJ and tandem. Using bismuth based low-temperature interconnection technology is not feasible for TW manufacturing unless the number of wires or ribbons can be largely reduced. However, this will increase the finger Rs losses and make the reduction in finger silver usage even more challenging. But on the other hand, due to a much lower ratio of Jmp to Vmp, there could be scope for tandem to reduce the number of wires without causing too much increase in the power loss. And beyond the scope of material availability of these scarce metals, we also need to pay attention to the environmental and socials impacts from the huge demand of abundant materials such as aluminum, steel and copper to ensure the development of the PV industry is sustainable and responsible.

7. Acknowledgments

The program has been supported by the Australian Government through the Australian Renewable Energy Agency (ARENA) and Australian Center for Advanced Photovoltaics (ACAP). The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

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C-O1. Other Crystalline Solar Cells such as III-V, CdTe and CIGS

Analysis of the solar resource, photocurrent, electricity production and greenhouse gases emission reduction of an experimental photovoltaic power plant to be placed in a university campus

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Abstract

Solar photovoltaic power plants are expanding rapidly all over the world. We analyzed in detail the solar radiation resource at the Urcuquí region, near 0° latitude in Ecuador, the photovoltaic merit factor, the photocurrent generated by solar radiation in typical solar cells of (mono and poly) Si, Germanium and perovskite, the mean annual electric energy produced and the corresponding avoided greenhouse gases emissions. Urcuquí has an annual averaged cloud coverage of (75.7 ± 3.5) % and an annual averaged global irradiance for 2015 equal to (984 ± 57) Wm⁻² in horizontal surface and with clear sky conditions. The photocurrent intensities calculated were: (34.9 ± 2.0) mAcm⁻², (26.9 ± 1.6) mAcm⁻², (26.5 ± 1.5) mAcm⁻² and (16.8 ± 1.2) mAcm⁻², for mono-Si, perovskite, poly-Si, and Ge solar cells, respectively. Finally, the installation of an experimental photovoltaic power plant of 1 MW_{peak}, can provide 1,410.1 MWh/year of electricity and reduce greenhouse gases emission by 483.88 TnCO_{2eq}/year.

Keywords: Solar photovoltaic power plant, Urcuquí, Ecuador, photocurrent, electric energy, greenhouse gases

1. Introduction

Solar energy is a clean and renewable energy source that it is available at a rather good level in Urcuquí (0.406° N, 78.172° W, 2100 m.a.s.l.), Ecuador, a high altitude site, even if the cloud coverage is important. The photovoltaic merit factor, i.e., the mean annual energy output for each kW_{peak} of photovoltaic power, is 1,640.1 kWh per kW_{peak} per year, derived from the Global Solar Atlas of World Bank Group database (Solargis). Since at this site, a University Campus (Yachay Tech) with a scientific and technological orientation is placed, we propose to install there a solar photovoltaic power plant based on solar panels made of different materials: (mono and poly) crystalline Si, Ge or perovskite, in order to have the possibility to investigate their behavior, in a geographical site with unique characteristics since it is placed at almost 0° latitude, with high global radiation, high UV radiation (related to material degradation), rather low annual mean temperature compared to desertic sites and rapid modification of solar irradiance incident on the solar photovoltaic panels, due to the particular type of clouds (mainly cumulus or similar ones) and consequently also rapid change of the electricity generated by the solar power plant.

In this work, first we present the atmospheric state, and then we present results for: a) the photocurrent produced by each solar photovoltaic material at Urcuquí University Campus, b) the electric energy that could be produced by a solar photovoltaic power plant, and c) the related reduction in the emission of greenhouse gases.

In order to calculate the photo-generated current of each type of solar cell, it is necessary to count with the solar spectral irradiance and the quantum efficiency of the cells. The former was calculated employing the SMARTS (Simple Model of the Atmospheric Radiative Transfer of Sunshine) model (Gueymard, 1995).

The SMARTS model is an algorithm implemented in Fortran language that predicts the global, direct and diffuse solar intensities, and the atmospheric component transmittances in the range of 280 to 4000 nm for each wavelength, as function of different entry (atmospheric and meteorological) parameters that will be introduced later. Since their calculations are in function of input data of the site of calculation, if the data are appropriate for the site, their results are very accurate. It is important to point out that the irradiances are calculated on a horizontal plane in clear sky situation.

With regard to the solar cells in particular, the more relevant property with respect to the production of electrical energy is the *external quantum efficiency* (EQE), that is a quantum efficiency that represents the ratio of the number of charge carrier collected and the number of *incident* photons (Ananda, 2017). The photo-generated current depends on EQE of the solar cell. In the present work, the four solar cells EQE are: (mono and poly) crystalline Si and Ge (Stark and Theristis, 2015; Salum et al., 2015) and perovskite (Kim et al., 2022). Only the Ge solar cell has complete response in the infrared (IR) range, whereas the silicon solar cells have responses in the visible and IR ranges and a small fraction in the UV range. In particular, perovskite has responses in UVA, visible and a small fraction in the infrared range.

In the work of Salum et al. (2015), the results showed ozone and AOD_{550nm} having some effect on perovskite solar cell photocurrent efficiency, no significant effect on Germanium-based solar cells and some little effect on Silicon cells. The relationship between the solar cell quantum efficiency and air temperature was reported, for example, by Adeeb et al. (2019); Singh and Ravindra (2012) and Radziemska, (2003). An analysis about the influence of temperature over the solar cell efficiency was carried out by Shaban (2020). Omubo-Pepple et al. (2013) found that the emission of aerosols (natural or anthropogenic) into the atmosphere decreases the solar flux that reaches the solar panel, and Bergin et al. (2017) found that the particulate matter not only affects the incident solar radiation when it overpasses the atmosphere, but also reduces the energy production due to its deposition on the solar photovoltaic panels. Dew formation can produce reduction of the energy production of solar cells (Simsek et al., 2021); however, a novel research of 2016 analyzed the possibility of generating electricity with the fall of raindrops (Tang et al., 2016). Similarly, Ghitas (2012) performed an analysis on the effects of variation in each range of solar spectrum on the electrical parameters of mono-Si solar cell. In turn, Leitão et al. (2020) analysed the effect of spectral solar irradiance on the efficiency of different types of solar cells (including Si, Ge and perovskite). Finally, the work of Sağlam and Görgülü (2015) indicates the cloud amount produces a decrease in the generation of solar photovoltaic power, except in particular situations where it can result in an enhancement of total and UV solar irradiance (Järvelä et al., 2018; de Andrade and Tiba, 2016; do Nascimento et al., 2019; Piacentini et al., 2003; Piacentini et al., 2011; Almeida et al., 2014). In particular, Emck and Richter (2008) studied the clouds effect over the global irradiance in sites with altitude above 1900 m.a.s.l. at low latitudes and they found global irradiance values over 1800 W/m².

Another source of solar data consultation is the Global Solar Atlas web page of World Bank. Here, the Global Photovoltaic Power Potential by Country can been obtained. Among other parameters, the available information is about the potential solar resource enable to be used in photovoltaic power plants in the world. A factsheet for each country can be download and very useful information for the present work is showed: specific photovoltaic power output, annual mean global solar horizontal irradiation and the optimum angle of inclination for Urcuquí, Ecuador. Also, area, population, electricity consumption per capita, PV equivalent area and other parameters are published.

2. Methodology

As presented in the Salum et al. work (2016), the procedure to calculate the photo-generated current consist in the following steps:

a- Obtain the incident spectral irradiance by means of a model or a measurement.

In the present work, we used the SMARTS model to modeling the solar total spectral irradiance in a place at solar noon.

b- Obtain the meteorological input data for the SMART model.

The analysis of meteorological parameters has relevance, since the photovoltaic panels are susceptible to variables such us the air temperature at 2 meters, relative humidity, and other atmospheric components. These data were

obtained from different satellite database:

- i- POWER/NASA database (https://power.larc.nasa.gov/). From this database, we obtained the following data: air temperature at 10 m, relative humidity, total column precipitable water and surface albedo.
- ii- OMI/NASA database. From this database, we obtained the ozone total column.
- iii- MODIS-Aqua Deep Blue/NASA database. From this database, we obtained the AOD_{550m} (aerosol optical depth to 550 nm).

c- Apply the External Quantum Efficiency (EQE) for each wavelength and each type of solar cell, in order to calculate the photovoltaic current (per unit area).

This calculation requires to make the product of the spectral surface density photovoltaic current and the solar cell EQE.

Also, as a result of the spectral solar irradiance calculations made with the SMARTS model, global and total UV irradiances for each month were obtained. These irradiances are calculated integrating the spectral solar irradiances in wavelength.

From the web page of the Global Photovoltaic Power Potential by Country (Global Solar Atlas of World Bank Group), once Ecuador was chosen as country, Specific photovoltaic power output, annual mean global solar horizontal irradiation and the optimum angle of inclination were obtained.

Another result obtained in the present work is the emissions of greenhouse gases reduction caused by the hypothetical implementation of a solar photovoltaic power plant.

3. Results

3.1 Photocurrent produced by each solar photovoltaic material at Urcuquí University Campus This objective needed to several steps. Following, each result is detailed.

3.1.1 Meteorological data

Figure 1 shows the annual evolution of average value of each month of air temperature and relative humidity at Urcuquí in 2015. The maximum (minimum) monthly average value of air temperature was 22 °C (19.9 °C) in September (January and December) 2015, and the maximum (minimum) monthly average value of relative humidity was 80.6 (50.8%) in December (August) 2015.



Fig. 1: Monthly mean evolution of air temperature (red line) and relative humidity (blue line) for a typical year (2015) at Urcuquí, Ecuador. Note: The line is a smoothing function connecting the points. Source: POWER/NASA.

Figure 2 shows the evolution of the monthly average total column ozone (in Dobson Units) for 2015. It can be seen that the atmospheric ozone has maximum values in August and September and maximum values in January and December. In this figure, the line represents a smoothing function.



Fig. 2: Annual evolution of Total column ozone in Urcuquí for 2015. Source: Power/NASA.



Fig. 3: Evolution of monthly average of AOD_{550nm} in the period 2003 to 2018, at Urcuquí. Source: Power/NASA



Fig. 4: Evolution of monthly average of cloud fraction in the period 2003 to 2018, at Urcuquí. Source: Power/NASA

In the case of the aerosol optical depth at 550 nm (AOD_{550nm}), it was obtained in the period 2003 to 2018 (Figure 3). The mean value is (0.196 ± 0.043) , being the maximum and minimum values: 0.364 and 0.111, respectively. This parameter has a particular importance because the aerosols influence the solar irradiance mainly at lower Visible and UV wavelengths that fall over the solar panels surface and consequently decreases the corresponding efficiency.

The cloud fraction for the same period of time was obtained from the satellite data base MERRA – 2 model/NASA (Figure 4). The monthly average cloud fraction at Urcuquí, Ecuador is (0.757 ± 0.035) .

According the used satellite database, the mean values of atmospheric parameters for 2015 in Urcuquí are presented in Table 1. These data were obtained in order to use the SMARTS model.

Table 1: Atmospheric parameters obtained from POWER/NASA for 2015 year for Urcuquí, Ecuador.

Parameters	Mean values		
Air temperature	(20.9 ± 0.7) °C		
Relative humidity	$(69\pm11)\%$		
Total column ozone	$(250.1 \pm 9.6) DU$		
AOD _{550nm}	(0.196 ± 0.043)		
Cloud fraction	(0.757 ± 0.035)		

3.1.2 Solar data

According to the Global Solar Atlas of the World Bank Group, the KWh of electricity that would be generated by a photovoltaic system with each KWpeak of installed capacity is the *Specific photovoltaic power output* (or PVOUT specific). In Urcuquí, $PV_{out} = 1640.1$ KWh.KWp⁻¹year⁻¹ with an annual mean global solar horizontal irradiation of 2040.4 kWh.m⁻² and an optimum angle of inclination of 2°.

The mean annual solar global irradiance at solar noon for a typical year (2015) in Urcuquí equals to (984 ± 57) Wm⁻² (from POWER/NASA data base).

After integrating, global and total UV irradiances were obtained, for each month in 2015 and for the same equatorial site (see Figure 5). The annual mean values of these irradiances are: (984 ± 57) Wm⁻² and (62.9 ± 8.4) Wm⁻², respectively.

The small difference (of 3.9%) between the mean annual irradiance satellite value (946 W m⁻²) and the model value (984 W m⁻²) is mainly due to the indetermination in the cloud attenuation.



Fig. 5: Annual evolution of global (blue line and circles) and UV (red line and circles) solar irradiances in Urcuquí.

3.1.3 Solar generated photocurrent

In order to determine the potential of solar energy as a renewable source in Urcuquí, Ecuador, first, the spectral solar

irradiance for Urcuquí incident on a horizontal plane for clear sky days was calculated. For this, it was used the SMARTS model with input data obtained from satellite database (aerosol optical depth, total ozone column, albedo, air temperature, and relative humidity). The spectral solar irradiance was calculated once per month (see an example for the day December 15th, 2015, corresponding to the red line in Figure 6).



Fig. 6: Typical spectral solar irradiance for the clear sky day December 15th, 2015, as an example (from SMARTS model) (with the following values of the parameters for this particular day: O₃ = 234.5 DU, AOD_{550nm} = 0.196, Cloud cover = 0 %), incident on a horizontal surface at Urcuquí, Ecuador (red line), the EQE for a perovskite cell (black line), spectral photocurrent intensity (blue line) and integrated photocurrent intensity (grated area). Source of the perovskite data: Kim et al., 2022.

The next step was the determination of the photon density, calculating for this purpose the ratio between the solar irradiance and the photon energy, for each wavelength.

Finally, the photo-generated current for each type of solar cell is obtained as the wavelength integral of the spectral photo-current intensity (blue grated area in Figure 6). This photo-current is determined as the multiplication of the photon density by the electron charge and by the EQE (black line in Figure 6). An example of the calculation performed for perovskite solar cells is shown in Figure 6, for the typical clear sky day December 15^{th} , 2015, at Urcuquí, Ecuador, at solar noon (=UT – 5 hours).



Fig. 7: Mean photocurrent of different solar cells for each month of the year (period January-December 2015), for Urcuquí, Ecuador: mono-Si (black bar), perovskite (red bar), poly-Si (blue bar) and Ge (magenta bar).

As a result of the previous calculation, we obtained one photocurrent per month. Figure 7 shows the comparison between the photocurrent generated by each of the four solar cells in different months of the year, in Urcuquí, Ecuador. As can be seen, mono-Si gives the highest mean photocurrent $(34.9 \pm 2.0) \text{ mAcm}^{-2}$, followed by perovskite $(26.9 \pm 1.6) \text{ mAcm}^{-2}$, poly-Si $(26.5 \pm 1.5) \text{ mAcm}^{-2}$, and finally Ge $(16.8 \pm 1.2) \text{ mAcm}^{-2}$. The annual mean relative percentage between each solar cell photocurrent and the mono-Si is: (76.9 ± 0.7) % for perovskite, (76.0 ± 0.3) % for poly-Si and (48.2 ± 2.1) % for Ge. The lowest value of the Germanium photocurrent density with respect to (mono and poly) Si and perovskite solar cells, is due to the particular behavior of its EQE, mainly concentrated in the infrared region of the electromagnetic spectrum, where the solar radiation is decreasing, in comparison with the visible range.

3.2 Electrical energy that could be produced by a solar photovoltaic power plant

We consider the possibility to install an experimental 1 MWpeak solar photovoltaic power plant, with panels made of different solar cells as described above, in about 1.5 Ha of the Yachay Tech University campus, at Urcuquí, Ecuador. So, the annually produced electricity will be:

 $E_{PV} = PV_{OUT} \cdot 1 MW_{peak} = 1640.1 MWh per year (eq. 1)$

with the PV_{OUT} value given in item 2.1.2 Solar data. Taking into account the losses of the system as 14%, due to inverter, internal transmission lines, DC/AC transformation, etc., the electricity annually produced will be 1,410.1 MWh per year.

3.3 Related reduction in the emission of greenhouse gases.

The avoided emissions of greenhouse gases (GHG) due to the solar photovoltaic power plant, can be obtained from the conversion coefficient between a unit of mixed electric energy (renewable and non-renewable) of Ecuador and a unit of emitted GHG, which is: $f_{E,GHG(Ecuador)}=0.343$ TnCO_{2,eq} per MWh (Parra Narváez, 2015). Therefore, the annual mass of avoided emissions is:

 $M_{GHG,FV} = f_{E,GHG(Ecuador)} \cdot E_{PV} \cdot 0.86 = 483.8 Tn CO_{2,eq} per year (eq. 2)$

were *Carbon Dioxide equivalent* ($CO_{2,eq}$) means that all other greenhouse gases (mainly Methane, CH₄ and Nitrous oxide, N₂O) are referred to CO₂.

4. Conclusions

We developed model calculations for the determination of the behavior of spectral solar irradiance (in clear sky situation) and the available annual photocurrent generated by different solar cells as part of an experimental Solar Power Plant, to be placed at an equatorial high altitude site, Urcuquí, Ecuador. The annual mean value of global solar irradiance incident at solar noon on a horizontal surface is (984 ± 57) W/m². A similar behavior is observed for the UV component, with an annual mean value of (62.9 ± 8.4) W/m².

With respect to the photocurrent intensities, the largest one corresponds to mono-Si solar cell with an annual mean value of (34.9 ± 2.0) mA/cm². The annual mean relative percentage between each solar cell photocurrent and the mono-Si is: (76.9 ± 0.7) % for perovskite, (76.0 ± 0.3) % for poly-Si and (48.2 ± 2.1) % for Ge.

In particular, due to the large contribution in Urcuquí, Ecuador, of cumulus clouds to the solar radiation enhancement effect, a detailed analysis of this phenomena is of interest, taking into account that specially perovskite solar cells degrade rapidly (in several months) with time exposure.

Also, we determined the annual mean of the electricity produced by a 1 MWpeak experimental photovoltaic minipower plant (with modules based on the 4 different cells) in a University Campus at Urcuquí, Ecuador as 1,410.1 MWh per year and the corresponding avoided emissions of CO_2 , resulting in a saving of 483.88 TnCO2_{,eq} per year. This mini-power plant can be employed, -besides the possibility of the electric supply of the University Campus, for doing research work and training of graduate and post-graduate students in the highly expanding field of Solar photovoltaic, -that can contribute to the world effort for mitigating the global warming (IPCC, 2013, 2018) and also in relation to solar cell degradation in an almost equatorial, high altitude site.

5. Acknowledgments

The authors like to thanks CONICET (Argentina), the National University of Rosario, Argentina and the Yachay Tech University, for partial support of the present work.

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Characterization of ZnO Films Doped by Erbium

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Abstract

Er-doped ZnO thin films were grown on fused quartz and *p*-Si substrates by radio-frequency magnetron sputtering method. The effect of post-deposition treatment at 600 - 900 °C on film properties was studied by scanning electron microscopy, energy dispersive x-ray spectroscopy and atomic force microscopy, X-ray diffraction analysis, optical transmittance, and the room-temperature photoluminescence measurements. All the films showed a (002) preferential orientation with the c-axis perpendicular to the substrate surface. The increase of annealing temperature changes some physical properties of ZnO films. The results obtained from both X-ray diffraction and photoluminescence spectra reveal that Er³⁺ ions successfully substitute for Zn²⁺ ions in the ZnO lattice. No impurity phase was found in Er-doped films. The doped ZnO films showed good transmittances (70–80%) in the spectral range of 370-2500 nm. Transmission spectra of as-deposited Er-doped ZnO films contain a wide absorption band in the near-infrared region. Photoluminescence spectra leage occurred. It was found that an increase in the annealing temperature leads to an increase in the photoluminescence intensity in the spectral range of 1.5 - 3.0 eV. Photoluminescence excitation spectra of Er-doped ZnO films contain a band with a maximum at ~ 3.40 eV which corresponds to the band gap energy of ZnO. Hot-Probe characteristics measured for as grown and Er-doped thin films showed that these materials have *n* type conductivity.

Keywords: ZnO thin films, erbium, magnetron sputtering, structural properties, photoluminescence

1. Introduction

Zinc oxide (ZnO) is a wide-gap semiconductor material that possesses a unique combination of optical, acoustic, and electrical properties and is extensively used in a number of optoelectronic devices, such as converters of surface acoustic waves (SAWs), solar cells, optical waveguides, laser reflectors, broadband filters, and liquid-crystal displays (LCDs) (Coleman et al., 2006; Mishra et al. 2015; Wang, 2004). This growing interest in ZnO stems from the possibility to use it in optoelectronics applications, which is made possible mainly due to its direct band gap of Eg $\sim 3.3 - 3.4$ eV at 300 K. It crystallizes at relatively low temperatures, easily processed utilizing chemical etching and has tunable properties by doping to achieve high optical transmittance and low resistance (Nickel and Terukov, 2005). It is known that ZnO exhibits two luminescence bands: a short wavelength band (UV region) and a broad long-wavelength band with the maximum in the green spectral range. The former is due to exciting recombination, whereas the latter is caused by native defects. The contribution of each recombination channel depends on the structural quality and fabrication conditions of ZnO materials. However, the monitoring of visible photoluminescence (PL) is challenging up to now. One of the ways to obtain controllable PL in a specific spectral range is doping with different elements. Additionally, the wide band gap of ZnO allows incorporating luminescent centers such as rare earth (RE).

In recent years, the interest in preparing ZnO thin films doped with lanthanide elements (Ln^{3+}) has increased due to the interesting properties that can be obtained by using 4f valence electron elements (Akazawa et al., 2014, Das et

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al., 2015, Kumar et al., 2017). It is well known that rare-earth ions (erbium, terbium, europium, thulium, and so on) are a special kind of photoactive centers with narrow emission lines and long emission lifetimes in various semiconductor materials. The trivalent rare earth (RE) elements have been tested as dopants resulting in high ZnO film conductivity and specific luminescence properties (Kumar et al., 2017). Among them, erbium (Er^{3+}) is a suitable candidate for the conversion of infrared to visible light due to its favorable electronic energy level structure (Akazawa and Shinojima, 2014; Kohls et al., 2002; Meng et al., 2011; Schmidt et al., 1998). Trivalent erbium has an incomplete 4f electronic shell that is shielded from the outer atomic environment by closed 5s and 5p shells. As a result, rather sharp optical intra-4f transitions can be achieved from erbium doped materials. The transition from the first excited state to the ground state in Er^{3+} occurs at an energy of 0.8 eV, corresponding to a wavelength of 1.54 μ m. This is an important telecommunication wavelength since standard silica-based optical fibers have their maximum transparency at this wavelength and extensively used as an eye-safe source in the atmosphere, laser radar, medicine, and surgery (Kenyon, 2002; Kumar et al., 2017). The studies of Er-doped ZnO (ErZO) thin films showed that the 1.54 µm luminescence would occur when the Er atoms are triply ionized and embedded in the ZnO hosts. It is allowing an effective energy transfer from the excited host electrons in the conduction band to the Er ions - a common indirect excitation mechanism for Er doped semiconductors (Polman, 1997). It has been demonstrated that Er acts as an optically active center if it is surrounded by oxygen forming a pseudo-octahedron structure (Kenyon, 2002; Kumar et al., 2017). This means that Er replacing Zn in the ZnO matrix forms Er_2O_3 and does not act as an optically active center. Therefore, an annealing treatment of thin films is required to change local structure of Er, forming clusters either in the ZnO matrix or at the grain boundaries.

Thin film growth parameters are largely affected by the deposition techniques and the process parameters. There are various deposition techniques available for preparing ZnO thin film (Coleman et al., 2006; Mishra et al. 2015; Wang, 2004). One of the methods for ZnO film fabrication is radio-frequency (RF) magnetron sputtering. It results in the formation of columnar ZnO film with a preferred orientation of c-axes perpendicularly to the substrate surface. However, comparison of the results obtained for thin films, as far as we know, sometimes is contradictory. At the same time, the type of substrate can affect the structure as well as Er incorporation into ZnO grains. Another important factor is the growth and annealing temperature for thin film formation.

In this work, the Er-doped ZnO films were grown on fused quartz and *p*-Si substrates by radio-frequency magnetron sputtering and the effect of thermal annealing at $600 - 900^{\circ}$ C on their structural and optical properties was investigated aiming at the fine-tuning of RE ion emission.

2. Experimental

ErZO thin films were grown by RF magnetron sputtering of nominally pure Zn and ErCl₃-targets in an argon atmosphere with oxygen (20% Ar and 80% O₂) at a pressure of 5×10^{-3} Torr on pure Si and fused quartz substrates. We used targets with erbium composition of 1% and 2% by mass. The power density applied to the cathode was 2.0 W/cm² and the deposition time was 60 min. Both types of substrates were placed on the same sample holder to obtain the layers grown under the same conditions. The substrate temperature was kept at 25 °C. Si wafers were etched in 10%-water HF solution to remove the thermal SiO₂ layer from their surface. Before the deposition, all substrates were submitted to the cleaning procedure in an ultrasonic bath for 5 min to remove mechanical pollution, then sent to cleaning in propanol for 5 min and drying with nitrogen flow. The thickness of all films investigated was about 600 - 700 nm. After the deposition, the wafers were cut into 1×1 cm² pieces. Isochronal (30 - 150 min) post-growth annealing was performed at 600, 750, and 900 °C in a conventional furnace in nitrogen flow.

XRD measurements of ZnO films were performed using Ultima IV X-ray diffractometer (Rigaku) in grazing incidence X-ray diffraction (GIXD) geometry at 1.0° of incident X-rays with CuK α radiation source scanned in the range of 10 - 80° at room temperature. The evaluation of the XRD spectra of the films was conducted using JCPDS data cards. Chemical composition and the depth profile of elements in the films were determined by energy dispersive X-ray spectroscopy analysis (EDX) and Auger electron spectroscopy (AES) using a CAMECA SX-100 and Perkin Elmer Physics Electronic 590, respectively. An Ar ion beam with energy of 5 keV was used for simultaneous sputter etching. Morphology was analyzed by scanning electron microscopy (SEM) using the JEOL 6400. The AFM experiments were carried out in Intermittent contact mode, using a Solver Nano, NT-MDT atomic force microscope with a 10 μ m × 10 μ m high resolution scanner with a vertical range of 2 μ m, z-axis resolution 0.027 nm, and an X-Y linearity mean error of less than 0.6 %. Sharp tips were employed for measurements; with a radius of curvature of less than 10 nm. Topographic 2D AFM images have been recorded with a resolution of 256 × 256 pixels over scanning areas of 4 × 4 μ m² and the Nanosurf Easyscan2 software program (v1-6-0-0) was used for image processing and roughness evaluation. The transmittance (T) spectra of the ErZO thin films onto quartz substrates were measured in the spectral range of 200 – 3000 nm using a Carry 500 Scan UV-Vis-NIR (Varian, USA) spectrophotometer.

Photoluminescence (PL) and photoluminescence excitation (PLE) measurements were carried out by employing a 1000 W Xe lamp as an excitation source combined with a grating monochromator (600 grooves/mm, focal length ~ 0.3 m). All measurements were performed at room temperature. The Hot Probe characterization method was used for the definition of a semiconductor type, p or n, for as grown and ErZO thin films.

3. Results and discussion

3.1. Elemental composition and morphology of the films

The composition of the thin films before and after the annealing was estimated from the EDX measurements and appeared to be invariable after the heat treatment. The chemical composition was determined by averaging the concentration values from 10 different points on the surface of the same film (Tab. 1). The EDX results show that the incorporation coefficient for Er⁺³ ions is low and reach approximately 1.5 %. The EDX spectrum of Er-doped films shows the signals of Zn, O, Er, Si, C, and Ca where the signals of Si, C, Ca are from the substrates. Elemental mapping of Zn, Er, and O, shows a homogeneous distribution of all components without any concentrated places at the surface (not shown here).

Sample	Substrate	Annealing temperature, ⁰ C	Zn, at. %	O, at. %	Er, at. %
i-ZnO	Si	25	49.9	50.1	
1-ErZO	Si	25	48.7	50.5	0.8
2-ErZO	Si	600	49.1	50.1	0.8
3-ErZO	Si	900	49.3	50.0	0.7
4-ErZO	quartz	25	49.2	49.3	1.5
5-ErZO	quartz	600	49.5	49.1	1.4
6-ErZO	quartz	900	49.1	49.4	1.4

Tab. 1: - Chemical composition of as-grown films i-ZnO and ErZO:Er films doped by erbium fabricated on silicon and fused quartz substrates

A similar elemental composition (Zn, O, Er in atomic %) of ZnO thin films has been confirmed by AES method. The spectra were analyzed over a range of kinetic energies from 100 to 1400 eV using the primary electron beam of energy 5.0 keV. As an example, Fig. 1 shows the depth profile of elements for the as-grown non-annealed 1-ErZO film. The homogeneous distribution of all elements Zn, O, and Er along the depth of films is seen from Fig. 1. A similar homogeneous elements distribution is also revealed for all investigated films on different substrates. This fact confirmed the high-quality of the deposited films with nearly ideal stoichiometry of Zn and O chemical elements. The measurements show that Er atomic concentration in ZnO is not exceeded 1.5 at. % at magnetron sputtering.

The surface morphology and cross-section images of the thin films were characterized by SEM. According to crystal growth mechanisms, the growing faces of crystallites correspond to the crystal shape at equilibrium and are determined by the orientation of the crystal. A growth competition can start among the neighboring crystals according to their orientation. The faster-growing crystals will grow over slower-growing ones. Once the competition proceeds towards the formation of the same type of crystal faces, they form the free surface. This competitive growth mode represents an orientation selection resulting in the competitive growth texture. For ZnO, stably preferential orientation is along to *c*-axis (Coleman et al., 2006). The thermodynamically stable phase of ZnO is wurtzite symmetry. From the cross-section SEM images (Fig. 2), Er-doped ZnO films exhibit good flatness and the crystal grain size is dependent on the substrate (silicon, quartz) and the deposition conditions.


Fig. 1: AES depth profile of chemical elements of ErZO films on silicon substrate



Fig. 2: Cross-section SEM images of as-grown ErZO films on quartz (a) and silicon (b) substrates

As seen the films are consisting of grains with a size of about $0.10 - 0.15 \,\mu$ m with the well-faceted structure without any porous, nearly smooth surface and the crystal grain size is dependent on the Er concentration. The ZnO:Er films fabricated on fused silica substrates consist of separate nanocrystallite with a bigger size. The difference in the morphology of as-grown and Er doped ZnO films after the annealing is reflected by the size and shape of grains. The films do not have a large number of grain boundaries due to the absence of Er ions at the grain boundaries. The annealing might have helped the grains to grow much bigger, since high-temperature annealing stimulates the migration of grain boundaries and causes the coalescence of more grains. Good crystallinity should help improve the optical and electrical properties of the films.

Fig. 3 shows the AFM images taken on the ZnO films with different Er concentration. As can be seen from the AFM images, the coatings produced in all types of reagents are continuous, with no visible pores or puncturing, and formed of pyramidal crystallites grown along the same direction orthogonal to the substrate surface.



Fig. 3: AFM images, at the scale of (4×4)µm², of (a) i-ZnO, (b) 1-ErZO and (c) 5-ErZO thin films

The increasing of the grain size of ZnO thin films prepared on different substrates with increasing Er concentration is clearly observed. The root mean square (RMS) roughness is 7.42, 12.26, and 26.73 nm for the films with Er concentration of 0.0 %, 0.8 %, and 1.5 %, respectively. Most probably the roughness increases could be related to the increasing of surface defects (such as valleys and hills) after layer depositions and thermal treatments.

3.2. X-ray diffraction (XRD) analysis

The typical XRD patterns of ErZO thin films are shown in Fig. 4(a). The scans for the films grown onto different substrates demonstrate two peaks at $2\Theta \sim 34.5^{\circ}$ and 72.4° , respectively. These peaks are caused by reflection from (002) and (004) planes of hexagonal phase crystalline ZnO (JCPDS 36–1451 card).



Fig. 4: Typical X-ray of powder diffraction pattern of ErZO thin films on different substrates (a) and XRD peak position (c) in dependence on the Er concentration (b)

The greater intensities of (002) peaks in respective patterns indicated that crystallites grow preponderantly oriented with c-axis normal to the substrate (column-like structure). As it is shown in (Coleman et al., 2006; Wang, 2004) the film grains, after their coalescence, grow mainly in the direction normal to the substrate surface. In the case of hexagonal crystalline structure, this direction will be one. Most of the closely packed structures have the lowest free surface energy in the (002) plane and crystallization favorably occurs in this direction. Experimental data indicate that single phase ErZO layers without any second crystalline phase, such as free Er or erbium oxide, inparticular, Er₂O₃ may be fabricated under technological conditions. The as-deposited ZnO films did not show any feature related to the Er₂O₃ phase, suggesting that Er atoms are either substitutionally replacing Zn in the ZnO lattice or segregated to the non-crystalline region in grain boundaries (Polman, 1997; Kenyon, 2002). Fig. 4(b) shows, that the (002) XRD peaks with the increasing Er concentration are shifted towards lower angles with respect to that for pure ZnO $(2\Theta = 34.42^{\circ})$. Films had 'c' parameter values slightly higher than that of ZnO powder material (c = 0.521 nm), indicating that the unit cells of thin films are elongated along the c-axis and the compressive forces were predominant. The 'c' lattice constant increases from 5.21 Å to 5.28 Å with increasing Er concentration from 0.0 to 1.5 at. %. As the ionic radius of Er^{3+} (0.89 Å) is larger than that of Zn^{2+} (0.74 Å) (Polman, 1997), the increase of this 'c' lattice constant indicates that Er^{3+} ions successfully substitute for Zn^{2+} ions in the ZnO lattice. The internal compressive stress in the films is assigned to the bombardment of energetic particles during the deposition and not to the thermal stress originating from the difference between the thermal expansion coefficient of the film and the substrate (Coleman et al., 2006; Nickel and Terukov, 2005).

On the other hand, when the samples were annealed, the microstructure of the films was not changed by the plausible oxidation of Er and presented the Er_2O_3 phase in the XRD patterns. The presence of the Er_2O_3 phase was not observed in the sample, associated either with the relatively small amount of Er atoms incorporated into the film (low doping level) or due to the absence of those phases for the employed deposition conditions. After the annealing, the peaks were shifted to higher diffraction angles and the films showed lattice parameters (*a* and *c*) slightly lower than the ideal values for undoped ZnO films. This suggested that the stress was changing from compressive to tensile. It is possible that the annealing temperature produced tensile stress due to the mismatch between thermal energy

coefficients when the films cooled down (Hodes, 2005). It was also observed that the annealing of films produces variation in the intensity of the main diffraction peak (002) and showed an increase in its intensity, which unequivocally indicates an enhancement of the film's crystalline arrangement. The average crystallite size in the direction of normal to the reflecting planes was increased after the annealing process.

3.3. Optical and photoluminescence study

With the aim of the band gap energy determination of different ErZO films fabricated on quartz substrates the measurements of reflectance spectra at room temperature have been performed. As an example, Fig. 5 shows transmission spectra of thin films prepared on these substrates.



Fig. 5: Transmission spectra and the dependence of α^2 vs hv for ErZO films on quartz substrates

As seen all films have a high value of transmittance ~ 70 - 80 % in wide spectral range 370-2500 nm, intensive interference fringes, and a relatively sharp edge of the intrinsic absorption which starts at less than 390 nm. The sharp decrease in the transmission spectrum below ~450 nm is related to the strong absorption of the photons in this region. Besides the interference fringes arising at the reflection from boundaries of a film-substrate and a film-air, the wide absorption band from 1.0 to 2.5 nm in the IR range of a spectrum, is seen. These experimental data confirmed the high quality of ErZO layers grown on quartz substrates. The shifting of intrinsic band edge in the ultraviolet spectral region and decreasing transmittance in the near-infrared region is observed for no annealed films in contrast to i-ZnO films. The absorption in 1.0 – 2.5 µm spectral region and high-energy shift of absorption edge are indicating strong doping effect of ZnO films by Er atoms. A similar behavior of optical spectra is observed for n-type highly doped semiconductors such as ZnO:Al (Coleman et al., 2006; Nickel and Terukov, 2005). This phenomenon may be explained by the Burstein-Moss effect. As seen, annealing at temperatures higher than 600 °C leads to a low-energy shift of intrinsic absorption edge and decrease in infrared absorption.

The transmission spectra presented in Fig. 5 were analyzed under the light of Tauc expression and the derivative spectroscopy technique. The absorption coefficient (α) was calculated by the expression of $\alpha = -\ln \tau/d$, where the film thickness is $d \approx 700$ nm. Tauc formula is related with the band gap energy (*Eg*) and the absorption coefficient (Pankove, 1971):

$$(\alpha h\nu) = A(h\nu - E_g)^n , \qquad (eq. 1)$$

where A and *n* are band tailing parameters and index, respectively. The *n* index is 2 for indirect and 1/2 for direct band gap energy characteristics. The Eq. (1) states that $(\alpha hv)^{l/n}$ vs. (hv) plot exhibits a linear region in the strong absorption region. The linear fitted line intersects the energy axis at the band gap energy value. The $(\alpha hv)^2$ vs. (hv) plots for ErZO films are shown in the inset of Fig. 5. Determination of *Eg* value is illustrated in the inset of Fig. 5 and it amounts to 3.62 eV and 3.22 eV for the as-deposited (4-ErZO) and after annealing (6-ErZO) films, respectively. These values are consistent with that measured from PLE spectra for the same samples.

The main attention was concentrated on the photoluminescence and photoluminescence excitation measurements of ZnO films prepared on different substrates. As an example, Fig. 6 shows the photoluminescence and photoluminescence excitation spectra of i-ZnO thin films grown on *p*-type Si substrate after 30 min and subsequent

annealing at temperatures of 600 $^{\circ}$ C, 750 $^{\circ}$ C, and 900 $^{\circ}$ C. The PL and PLE spectra were taken at room temperature. It is clearly seen that PL spectra contain two broad intense bands with maxima at 2.43 eV (green emission 510 nm) and at 1.94 eV (yellow emission at 640 nm). The experiments show that the relative intensity of green and yellow emissions increases with annealing temperature reaching a maximum at 900 $^{\circ}$ C.



Fig. 6: PL and PLE spectra of i-ZnO thin films for different annealing temperature

The annealing time in the range from 30 up to 150 min for each temperature, as indicated in Fig. 6, also increases the intensity of the bands at 2.43 eV and 1.94 eV. These two bands may be referred to oxygen vacancy (V_0^+) and oxygen interstitial (O_i^-) respectively. The changes in the relative intensity of both bands are observed at annealing temperature variation. This effect indicates redistribution of radiative recombination channels of nonequilibrium charge carriers. Fig.6 shows that the green-dominant emission at lower annealing temperature (600 and 750 °C) is switched to yellow emission at higher annealing temperature (900 °C). This is issued by the competition between the formation of V_0^+ and O_i^- defects. A broad PLE band with a maximum at 3.40 eV was observed for all investigated i-ZnO films. The energy maximum at 3.40 eV \pm 0.05 eV corresponds to the optical band gap energy of ZnO material. Fig. 7 shows the PL spectra taken at room temperature for Er-doped ZnO thin films on Si substrate. The deposited films were annealed at different temperatures. When the annealing temperature increased in the range 600 – 900 °C high strength deep-level emission in the spectral region 1.5 – 3.0 eV has been observed.



Fig. 7: PL and PLE spectra of ErZO thin films for different annealing temperature

It can be seen that the peak intensity and energy position of deep-level emission varies with annealing temperatures. In particular, ErZO films annealed at 900 °C show only one broad PL band. The appearance of this band may be related to the formation of defects induced by Er atom incorporation in the ZnO lattice. The rate of formation point

defects is low for ErZO films annealed at low temperature ~ 600 °C. More defects responsible for the radiative transitions introduce into the films for the temperatures higher than 600 °C. In addition to thermal treatment, doping by Er atoms plays an important role in the mechanism responsible for the deep-level luminescence as well. It is notable that the yellow emission decreases with increasing annealing temperature for Er-doped ZnO thin films. One cause is most likely due to the formation of Er - V₀ bonds in ErZO films. Another possibility of the variation in the intensity of the yellow band at ~ 1.94 eV can be ascribed to the additional formation of interstitial oxygen. The probability of the electron charge transfer from localized impurity states to the conductive states is increased due to the potential fluctuation of Er impurities in ZnO films. We must speculate that both probable mechanisms are responsible for the increase of green emission. Further investigations are needed to verify this point of view. The PLE spectra of Er-doped films also contain broad band with a maximum at 3.40 ± 0.05 eV which corresponds to the optical band gap energy of ZnO.

It is well known that Er^{3+} ions (Polman, 1997; Kenyon, 2002; Kumar et al., 2017) are responsible for the visible luminescence in the spectral region 500 – 600 nm (2.07 – 2.48 eV). We cannot have detected sharp Er^{3+} related lines in the green region of spectra due to high-intensity emission related to intrinsic point defects such as O_i and V_O in ZnO material. Instead that we detected infrared luminescence of erbium in ZnO films (Fig. 8-9).



Fig. 8: PL and PLE spectra of ErZO thin films for different annealing temperature



Fig. 9: PL and PLE spectra of ErZO thin films on quartz substrate for different annealing temperature

It is clearly seen that ErZO films exhibited 1.54 (0.81 eV) μ m Er³⁺ photoluminescence (Schmidt et al., 1998, Wang et al., 2006). This fact strongly suggests that Er³⁺ ions were incorporated in the ZnO lattice during the magnetron

sputtering process. The Er emission mechanism under indirect excitation is generally explained using an energy transfer model (Kenyon, 2002; Kumar et al., 2017). In the thin film and/or bulk counterparts of Er doped ZnO, the necessity of annealing to obtain the 1.54 μ m luminescence is explained by Er site activation. It has been found that the higher order O coordination around the Er decreased the PL intensity, which could be significantly improved when the local structure of the Er–O cluster changed to a pseudo-octahedron with C_{4y} symmetry (Ishii, 2001).

The PLE spectra of the infrared luminescence of Er-doped ZnO films on different substrates as a function of excitation wavelength showed that infrared Er^{3+} related emission may be excited by the band-to-band mechanisms in ZnO material as well as upper above gap excitation (Fig 8-9). The relatively intense broad band at 3.2 eV has been found in the PLE spectra for the different stages of the annealing.

A more interesting experimental finding is the efficient excitation of Er^{3+} -related emission near 1.54 µm (0.81 eV) throughout the band at 3.2 eV in comparing with band-to-band optical transition in PLE spectra of ErZO thin films. The band at 3.2 eV in PLE spectra (Fig. 8 and Fig. 9) may be attributed to the optical transitions on Er-O defects with relatively shallow energy levels in thin films (Polman, 1997; Kenyon, 2002; Kumar et al., 2017). An increase in the intensity of the PLE band at 3.2 eV with increasing annealing temperature results from the increasing concentration of structural Er - O defects and the formation of impurity energy band with shallow levels.

The conventional Hot Probe characterization method was used for the definition of a semiconductor type, p or n, by identifying the majority of the charged carriers by the sign of the measured voltage. Hot-Probe characteristics measured for as grown and ErZO thin films demonstrated that these materials have n type conductivity.

4. Conclusions

The effect of different atomic contents of Er⁺³ ions on structural, optical, and photoluminescence properties of ZnO films grown on fused quartz and p-Si substrates was studied by different experimental techniques. All investigated films were found by XRD to have a polycrystalline wurtzite type structure and exhibit (002) preferential orientation with the c-axis perpendicular to the substrate surface. As the annealing temperature increased, some changes in the physical properties have been observed. The change of the lattice parameters indicates that dopant ions substituting Zn ions were incorporated into the ZnO lattice. The doped ZnO films showed good transmittances (70-80%) in the spectral range of 370-2500 nm. Transmission spectra of as-deposited Er-doped ZnO films contain a wide absorption band in near-infrared region. The annealing at temperatures higher than 600 °C in nitrogen flow of these films leads to the disappearance of this band and to a low-energy shift of intrinsic absorption edge. After post-annealing treatment of ErZO films green and near 1.54 μ m PL emission related to intra-4f shell of Er³⁺ ions is observed. The relatively intense broad band at 3.2 eV has been found in the PLE spectra for the different stages of the annealing and may be attributed to the optical transitions on Er-O defects with relatively shallow energy levels in ZnO:Er material. The PLE spectra of ErZO thin films on different substrates also contain broad band with a maximum of 3.40 ± 0.05 eV which corresponds to the band gap energy of pure ZnO. As grown and Er-doped films have *n* type conductivity. Our results indicate that Er³⁺ ions are an effective co-doping element for ZnO films which can be used for application in thin film devices, laser and display technologies. The high structure quality of the Er doped thin films and the room temperature 1.54 μ m (0.81 eV) luminescence make them promising candidate to serve as functional units for applications in future optical communications.

5. Acknowledgments

Financial support from the Belarusian Republican Foundation for Fundamental Research, grant № T20UK-022, is gratefully acknowledged. The part of the work has been finased by the Belarusian State Programme for Research «Physical Material Science, New Materials and Technologies». The authors of this work are grateful to Affiliate RDC "Belmicrosystems" JSC "INTEGRAL"-"INTEGRAL" Holding Managing Company for EDX and SEM studies of thin films.

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Overview of Concentrator Solar cells and Analysis for their Non-radiative Recombination

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Abstract

Concentration photovoltaics have great potential of higher efficiency and lower cost compared to conventional crystalline Si and thin-film solar cells. Although excellent results for concentrator solar cells such as 27.6%, 30.5%, 44.4% 47.1% with GaAs InGaP/GaAs/InGaAs 3-junction and Si. and AlGaInP/AlGaAs/GaAs/GaInAs/GaInAs/GaInAs 6-junction concentrator cells have been demonstrated, there are still problems to be solved. This paper overviews concentrator solar cells. In addition, this paper presents analytical results for efficiency potential of concentrator solar cells based on analysis of non-radiative recombination loss in concentrator solar cells. Concentrator Si, GaAs, CIGS and InGaAs/InGaAs 3-junction solar cells have efficiency potential of more than 34%, 36% 31% and 50%, respectively, by realizing external radiative efficiency of 20% and reducing series resistance. This paper also presents our recent approaches for photovoltaicpowered vehicle applications and static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module with efficiency of 32.84%, and so forth.

Keywords: Solar Cells, Concentrator, Efficiency, Si, GaAs, multi-junction, non-radiative recombination

1. Introduction

The development of high-performance solar cells offers a promising pathway toward achieving high power per unit cost for many applications. Substantial increases in conversion efficiency can be realized by using concentrating solar cells rather than solar cells under one-sun operation (Yamaguchi and Luque, 1999). According to overview by Swanson (2003), work on concentrating photovoltaics as a means to reduce cost began in the early 1960s. However, the critical issues to be solved are 1) reducing series resistance to enable efficient handling of the large currents involved, and 2) to maintain low-enough temperature rise by heat dissipation. As a results of conducting R&D Programs under DOE, EC, and NEDO, conversion efficiencies of concentrating solar cells were improved significantly as shown Fig. 1.

In this paper, we describe potential of high-efficiency and low-cost of concentrating solar cells and key technologies for realizing high-efficiency concentrating solar cells. In this paper, our recent approaches for photovoltaic-powered vehicle applications, especially static low concentration photovoltaics are also presented.

2. Overview for concentrator Si, GaAs, CIGS and InGaP/GaAs-based multi-junction solar cells

Figure 1 summarizes chronological improvements in conversion efficiencies of Si, GaAs, CIGS and III-V compound multi-junction solar cells measured under 1-sun operation by using the global AM1.5 spectrum (1000 W/m^2) at 25_°C (IEC 60904-3: 2008 or ASTM G-173-03 global) (NREL) and measured under concentration operation by using the ASTM G-173-03 direct beam AM1.5 spectrum at a cell temperature of 25 °C (NREL) and future efficiency predictions of those solar cells (original idea by Professor Goetzberger et al. (2002) and modified by Yamaguchi et al. (2018)). The function chosen here (eq. 1) is derived from the diode equation):

 $\eta(t) = \eta_L \{1 - \exp[(a_0 - a)/c]\}.$ (eq. 1)

where $\eta(t)$ is the time-dependent efficiency, η_L limiting asymptotic maximum efficiency, a_0 is the year for which $\eta(t)$ is zero, a is the calendar year and c is a characteristic development time. Fitting of the curve is done with three parameters which are given in Table 1. For example, 55% for η_L , 15 for a_0 and 1986 for c were used in the case of III-V compound multi-junction solar cells for terrestrial use. The function can be fitted relatively well to the past development of best laboratory efficiencies of various solar cells under 1-sun and concentrator conditions, although no fitting parameters for concentrator CIGS solar cells are listed in Table 1 because of a few present data.



Fig. 1: Chronological efficiency improvements of crystalline Si, GaAs, III-V compound multi-junction solar cells and CIGS solar cells under 1-sun and concentrator conditions.

Solar cell	Illumination	$\eta_{\rm L}$	с	a ₀
	condition			
Single-crystal Si	1-sun	29	26.8	1947.2
Single-crystal Si	concentration	30	15	1965
GaAs	1-sun	30	20	1953
GaAs	concentration	33	20	1960
CIGS	1-sun	26.5	25	1968
CIGS	concentration	-	-	-
III-V multi-junction	1-sun	43	17	1975
III-V multi-junction	concentration	55	15	1986

Table 1: Fitting parameters for different technologies

3. Analysis for efficiency potential and non-radiative recombination of concentrator Si, GaAs CIGS and III-V 3-junction solar cells

Figure 2 shows concentration dependence of 27.6% efficiency Si concentrator solar cell reported by Amonix (Slade and Garbousgain, 2005), 44.4% efficiency InGaP/GaAs/InGaAs 3-junction concentrator solar cell reported by Sharp (Sasaki et al., 2013, Yamaguchi et al., 2016), 28.8% efficiency GaAs concentrator solar cell reported by FhG-ISE (Schilling et al., 2018) and 23.3% efficiency CIGS concentrator solar cell reported by NREL (Ward et al., 2014), and calculated by using eqs. 2 – 6. Although quite good agreement between calculated and experimental efficiency results of Si, GaAs and InGaP/GaAs/InGaAs 3-junction concentrator solar cells under concentrator condition of less than 100-suns, reduction in conversion efficiency of concentrator solar cells under

high concentrator condition is thought to be occurred due to series resistance and temperature rise. In the case of CIGS concentrator solar cells, under high concentrator condition of more than 20-suns, fill factor degrades because of higher series resistance.



Fig. 2: Comparison of calculated and experimental efficiencies of Si concentrator solar cell reported by Amonix, InGaP/GaAs/InGaAs 3-junction concentrator solar cell reported by Sharp, GaAs concentrator solar cell reported by FhG-ISE and CIGS concentrator solar cell reported by NREL as a function of concentration ratio.

In order to realize higher efficiency of concentrator solar cells, improvements in short-circuit density Jsc, opencircuit voltage Voc and fill factor FF are substantially necessary. One of problems to attain the higher efficiency solar cells is the higher minority-carrier lifetime in various materials. Non-radiative recombination loss of various solar cells were evaluated by external radiative efficiency (ERE) and open-circuit voltage Voc is expressed by (Rau 2007, Green, 2012, Yao et al., 2015, Yamaguchi et al., 2017, 2018a).

 $V_{oc} = V_{oc,rad} + (kT/q)\ln(ERE), \text{ (eq. 2)}$

where the second term shows non-radiative voltage loss, and $V_{oc, rad}$ is radiative open-circuit voltage.

Resistance loss of various solar cells were estimated by fill factor FF

 $FF \approx FF_0(1-r_s)(1-1/r_{sh}) \approx FF_0(1-r_s-1/r_{sh})$, (eq. 3)

where r_s are normalized series resistance and normalized shunt resistance r_{sh} , respectively and given by

 $r_s = R_s/R_{CH}$, (6) $r_{sh} = R_{sh}/R_{CH}$, (eq. 4)

The characteristic resistance R_{CH} is expressed by (Green, 1998)

 $R_{CH} = V_{oc}/I_{sc}$. (eq. 5)

Ideal fill factor FF₀ used in the calculation is empirically expressed by (Green, 1998),

 $FF_0 = [v_{oc} - ln(v_{oc} + 0.72)]/(v_{oc} + 1), (eq. 6)$

where v_{oc} is normalized open-circuit voltage and is given by

$v_{oc} = V_{oc}/(nkT/q), (eq. 7)$

In the calculation, highest values obtained were used as Jsc. Voc and FF were calculated by equations eq. 2 - eq. 7 and conversion efficiency potential of various solar cells were calculated as a function of ERE.



Fig. 3: Calculated efficiencies of Si, GaAs, CIGS and InGaP/GaAs/InGaAs 3-junction solar cells under 1-sun and concentrator operations as a function of ERE (external radiative efficiency) in comparison with state-of-the-art efficiencies of those solar cells under 1-sun and concentrator operations.

Figure 3 shows calculated efficiencies of Si, GaAs, CIGS and InGaP/GaAs/InGaAs 3-junction solar cells as a function of EREs in comparison with state-of-the-art efficiencies of Si, GaAs, CIGS and InGaP/GaAs/InGaAs solar cells under 1-sun and concentrator operations (Sasaki et al., 2013, Yamaguchi et al., 2016, Green et al., 2021).

Si concentration solar cells have efficiency potential of more than 34% by realizing ERE of 20% from about 0.2%.

Efficiencies of 26.7% and 27.6% (Green et al., 2021) have been demonstrated with single-crystalline Si solar cells under 1-sun and 92.3-suns concentrator operations, respectively. Si solar cells have potential efficiencies of more than 28.5% (ERE: from 5% to 20%) and 34% (ERE: from 0.2% to 20%) under 1-sun and concentrator operations, respectively,.

Efficiencies of 29.1% and 30.5% (Green et al., 2021) have been demonstrated with GaAs solar cells under 1-sun and 258-suns concentrator operations, respectively. GaAs solar cells have potential efficiencies of more than 30% (ERE: from 22.5% to 50%) and 36% (ERE: 1-5% to 50%) under 1-sun and concentrator operations, respectively.

Efficiencies of 23.35% and 23.3% (Green et al., 2021) have been demonstrated with CIGS solar cells under 1sun and 14.7-suns concentrator operations, respectively. CIGS solar cells have potential efficiencies of more than 26.5% (ERE: from 5% to 30%) and 31% (ERE: from 1-5% to 30%) under 1-sun and concentrator operations, respectively.

Efficiencies of 37.9% and 44.4% (Sasaki et al., 2013, Yamaguchi et al., 2016, Green et al., 2021) have been demonstrated with InGaP/GaAs/InGaAs 3-junction solar cells under 1-sun and 302-suns concentrator operations, respectively. The 3-junction solar cells have potential efficiencies of more than 42% (ERE: from 5% to 40%) and 50% (ERE: from 5% to 40%) under 1-sun and concentrator operations, respectively.

Figure 4 shows calculated result for concentration ratio at maximum efficiency as a function of area series resistance product of GaAs single-junction and InGaP/GaAs/Ge 3-junction concentrator solar cells (Green et al., 2021, Yoshida et al, 1983, Partain, 1995) Designing low series resistance of concentrator solar cells with area series resistance product of less than $50m\Omega cm^2$, $15m\Omega cm^2$ and $5m\Omega cm^2$ at 100-suns, 300-suns and 1000-suns, respectively is necessary for realizing high efficiency.



Resistance area product (mΩcm²)

Fig. 4. Calculated result for concentration ratio at maximum efficiency as a function of series resistance of GaAs single-junction and InGaP/GaAs/Ge 3-junction concentrator solar cells.



Fig. 5: Possible conversion efficiencies of single-junction and multi-junction solar cells calculated in the case of external radiative efficiebcy (ERE) of 100% and 1% in comparison with experimentally realized efficiencies for 1-sun intensity and under concentration.

Figure 5 summarizes efficiency potential (Phillips and Bett, 2014, Yamaguchi etal., 2021b) of single-junction and multi-junction solar cells calculated in the case of external radiative eficiency (ERE) of 100% and 1% in

comparison with experimentally realized efficiencies (best efficiencies reported) (Green et al., 2021) for 1sun intensity and under concentration. In the ideal case (ERE=100%), efficiency of 40%, 61% and 69% under concentration is expected with single-junction, 3-junction and 6-junction solar cells, respectively. Because concentrator solar cells show relatively lower ratio between 68% and 76% of the ideal values compared to those (between 76% and 90%) of solar cells under 1-sun operation, further studies of concentrator solar cells are necessary.

4. Our recent approaches for PV-powered vehicle application

Development of high-efficiency solar cell modules and new application fields are significant for the further development of PV and the creation of new clean energy infrastructure based on PV. Notably, the development of PV-powered vehicle applications is desirable and very important for this end. This paper also presents our recent approaches for PV-powered vehicle applications: Demonstration car using Sharp's high-efficiency III-V 3-junction solar cell modules has shown longer distance driving compared to vehicles installed with Si solar cell modules. Figure 6 shows practical data regarding the driving distance of Toyota Prius 2017 (Yamaguchi et al, 2021a), Toyota Prius 2019 demonstration car (Yamaguchi et al, 2021a) and Sono Motors Sion (Sono Motors)as a function of module efficiency and solar irradiance in comparison with calculated results of driving distance by assuming electric mileage of 9.35km/kWh and system charging efficiency of 81.2% without cell temperature correction.

The results suggest importance of high-efficiency solar cell modules, module nominal power and longer electric mileage (that is light-weight car) because Toyota demonstration car installed with III-V 3-junction solar cell module of about 30.9% efficiency has demonstrated 29.1km/day driving (Yamaguchi et al, 2021a) at an average solar irradiance of 4.1kWh/m²/day, contrary to Sono Motor Sion installed with Si back contact solar cell module of about 22% efficiency that has shown 18-19 km/day driving (Sono Motors) at the similar solar irradiance as seen in Fig. 6. However, cost reduction in III-V 3-junction solar cell modules is necessary.



Fig. 6: Practical data regarding the driving distance of Toyota Prius 2017, Toyota Prius 2019 (demonstration car) and Sono Motors Sion as a function of module efficiency and solar irradiance in comparison with calculated results of driving distance by assuming electric mileage of 9.35km/kWh and system charging efficiency of 81.2%.

As an approach for cost reduction of high-efficiency multi-junction solar cells, we are studying on static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module. Most recently, we have achieved 32.84%



efficiency with static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module (area of 10.76 cm²) as shown in Fig. 7 (Sato et al, 2020)].

(a) Fig. 7: (a) Photo and (b) current-voltage curve of prototype static low concentrator module with III-V based triple-junction solar cell.

5. Summary

This paper overviews concentrator photovoltaic (CPV) cells such as crystalline Si CPV cells, GaAs CPV cells and III-V compound multi-junction CPV cells. In addition, this paper presents analytical results for efficiency potential of CPV cells based on analysis of non-radiative recombination loss in CPV cells.

- 1) Si concentration solar cells have efficiency potential of more than 34% by realizing external radiative efficiency (ERE) of 20% from about 0.2%.
- 2) GaAs concentration solar cells have efficiency potential of more than 36% by realizing ERE of 50% from

about 1 - 5%.

- InGaP/GaAs/InGaAs 3-junction concentration solar cells have efficiency potential of more than 50% by realizing ERE of 40% from about 5%.
- CIGS concentrator solar cells have efficiency potential of more than 31% by realizing ERE of 20% from about 1-5%.

This paper also presented our recent approaches for photovoltaic-powered vehicle applications. Demonstration car using Sharp's high-efficiency III-V 3-junction solar cell modules, As an approach for cost reduction of high-efficiency multi-junction solar cells, we are studying on static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module. Most recently, we have achieved 32.84% efficiency with static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module (area of 10.76 cm²).

Acknowledgments

The authors thank members in the NEDO, METI and EC, and to Prof. A. Luque, Prof. Y. Okada, Prof. M. Sugiyama, Dr. A. Bett, Dr. T. Takamoto, Dr. G. Sifer, Dr. Y. Hishikawa, Prof. G. Sala Prof. N.J. Ekins-Daukes and other collaborative researchers who have contributed to the "EU-Japan Collaborative Research on Concentrator Photovoltaics". In addition, MY thanks to Prof. A. Yamamoto, Dr. H. Sugiura, Prof. K. Ando, Dr. C. Amano, Prof. S. Katsumoto, and other former members of the NTT labs., Dr. M. Al-Jassim and Dr. R. Ahrenkiel, NREL, and Dr. M. Yang, Dr. M. Imaizumi, Dr. S. Taylor, Dr. A. Kahn and Dr. N. Dharmarasu, former membrs of the Toyota Tech. Inst. Drs. E. Ikeda, T. Agui, H. Kurita and M. Ohmori, Japan Energy, Drs. T. Yamada, T. Tanabe, Matsubara and S Takagishi, Sumitomo Elec., Drs. K. Takahashi and T. Unno, Hitachi Cable, Drs. M. Kondo and H. Uozumi, Daido Steel, Prof. Y. Kemmoku, Toyohasi Sozo College, Dr. T. Egami, T. Hisamatsu and Y. Miyazaki, Daido Metal for their contribution to intitial stage of studies.

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C-05. Heterostructures on other s.c

Characterization of nanostructured CuO thin films grown with microwave activated chemical bath deposition when process is repeated for thickness increase

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Abstract

Nanostructured CuO shows perspectives as solar cell and water splitting material because of bandgap value and properties dependence on the employed technology. CuO films deposited with microwave activated chemical bath deposition show interesting nano-morphology and characteristics. This technique is simple and inexpensive; it requires less than 5-minute-long deposition time plus temperature below 75 °C - conditions desirable for solar energy capture devices. When processes are repeated for thickness increase, important changes of CuO films characteristics occur. X-ray diffraction and Raman spectroscopy reveal morphological and structural properties. Optical transmission and reflection experiments demonstrate corresponding changes in bandgap value.

Keywords: Nanostructured CuO, MW-CBD, solar cell, water splitting

1. Introduction

CuO nanostructured films are currently studied for applications in solar cells (Wu et al, 2018) and water splitting (Li et al, 2019). Material characteristics depend on nano-morphologies which result from different deposition technologies and bandgap increases from 1.2 eV to over 1.5 eV (Ray et al, 2017) when nanocrystal size decreases. This makes nano-CuO very interesting for band engineering required to improve solar devices characteristics. On the other hand, novel microwave-activated chemical bath deposition (MW-CBD) allows semiconductor growth rather than deposition on the FTO conducting glass due to preferential heating of the substrate, which creates a temperature gradient (Rassaei et al, 2009). MW-CBD allows to grow films at temperatures below 100 °C and in less than 5 minutes (Gonzalez et al, 2020). MW-CBD is employed to grow CuO films using one, two and three microwave processes to increase layer thickness. Their characteristics are analyzed using optical transmittance, diffused reflection, scanning electron microscopy (SEM), X-ray diffraction (XRD) and Raman spectroscopy

2. Experimental part

2.1 Samples preparation

Copper oxide films were deposited on FTO conducting glass (TEC-15 – Pilkington). FTO pieces $(2.0 \times 1.5 \text{ cm}^2)$ were cleaned ultrasonically with 2-propanol and then with distilled water (during 3 minutes each). The precursor solution was prepared by mixing 1 part of 0.2 M Cu (II) acetate aqueous solution and 9 parts of ethylene glycol (boiling temperature T = 197.6 °C). The substrate was placed vertically in 15 cm³ of the precursor solution at the center of a microwave oven working at 2.45×10^9 Hz (cavity volume: $28 \times 28 \times 21 \text{ cm}^3$). The glass with the precursor solution and substrate was placed at the center of another glass filled with water; this one has a larger diameter in order to regulate temperature. The microwave power used was 0.7 kW. To guarantee direct growth on the substrate, microwave irradiation was applied during a short time while no nucleation in the precursor solution appeared. Continuous microwave irradiation time did not exceed 2 minutes. The deposition process could be repeated to obtain thicker layers, always starting from room temperature. The precursor solution temperature after microwave irradiation never exceeded 75 °C as measured with a digital infrared thermometer. Following the MW-

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To analyze technology effects different sample types were fabricated using 0.2M or $0.1M \text{ Cu}(\text{AcO})_2$ solution concentration and pH6 or pH7 of the precursor solution. Samples were identified by ST, 1CT, 2CT and 3CT for one MW-CBD process but no heat treatment, one MW-CBD plus heat treatment, two MW-CBD plus heat treatment and three MW-CBD plus heat treatment, respectively. The sample number follows this ID plus pH and Cu(AcO)₂ solution concentration values.

2.2 Samples characterization

The X-ray diffraction (XRD) pattern was obtained in a Bruker diffractometer, D2-Phaser model, on Bragg-Brentano condition using the $K_{\alpha 1}$ radiation of copper and a Lynx-eye detector. The Raman spectrum was recorded in a Thermo Scientific DXR Raman Microscope equipment using laser radiation of 455 nm and 0.5 mW of power, focused by a 50X objective with 0.75 of numerical aperture, integration time of 5 s per scan and 10 scans per spectrum. Optical transmission and reflection spectra were obtained in a Cary 5000 UV-Vis-NIR spectrophotometer, Agilent, equipped with a "Praying Mantis" accessory.

3. Results and discussion

Figure 1 shows photos of typical CuO thin films obtained using MW-CBD. The first lighter color one corresponds to a film obtained using one MW-CBD process and no heat treatment. After heat treatment a one-process sample becomes darker (second photo). This could be due to Cu species that were not fully oxidized to CuO or to quantum size effects. This will be discussed later. Even darker samples are obtained when using more than one MW-CBD process and heat treatment. This is due to sample thickness increase as further experiments also show. Samples shown were obtained with a 0,2M Cu(AcO)₂ concentration and pH6 of the precursor solution. Gradual darkening with heat treatment and number of processes is also observed when using other concentration and pH values.





In figure 2 scanning electron microscopies show the grain morphology of CuO films obtained when using MW-CBD. One can observe that the grain size increases when using a more concentrated $Cu(AcO)_2$ solution.



Fig. 2: Scanning electron microscopy (SEM) images (a) concentration of Cu(AcO)₂ solution 0.1 mol/l (1CT-P46-pH6-0.1), (b) concentration of Cu(AcO)₂ solution 0.2 mol/l (1CT-P8-pH6-0.2)

In figure 3 one can observe that typical optical transmittance experiments for a single process, with and without heat treatment, plotted as log T⁻¹ show practically no light absorption in the 500-800 nm range where CuO absorbs light (log T⁻¹ is not exactly equal to optical absorption due to reflection losses, which should be relatively small). This could mean that Cu₂O is deposited first, rather than CuO but this could not be true for one-process samples with heat treatment above 450 °C. At this temperature, Cu₂O necessarily oxidizes to CuO. Then, quantum size effects due to fine nano-morphology requiring higher SEM resolution (see Gonzalez et al, 2020) could explain it. Films made with two and three MW-CBD processes plus heat treatment show a higher absorption. This indicates that thicker films are obtained. One can observe also, that curves show optical absorption starting at higher wavelengths (lower energies) for samples with three MW-CBD processes. It is well known that the absorption edge depends on the bandgap value.



Fig. 3: Typical dependence of log T⁻¹ with wavelength from transmittance experiments which allows to analyze light absorption by films. Spectra correspond to samples 1ST-P58-pH7-0.2, one MW-CBD but no heat treatment; 1CT-P38-pH7-0.2, one MW-CBD with heat treatment; 2CT-P39-pH7-0.2, two MW-CBD with heat treatment; 3CT-P40-pH7-0.2, three MW-CBD with heat treatment

The Kuvelka-Munk function F(R) obtained from diffused reflection spectra, is shown in figure 4 for samples with different number of MW-CBD processes and fabricated using precursor solution with concentration 0.2 M Cu(AcO)₂ and pH6. The wavelength value at which samples start reflecting significantly increases with the number of processes indicating different bandgap values.



Fig. 4: Kubelka-Munk function F(R) obtained from diffused reflectance experiments for samples with a different number of processes: 1ST-P11-pH6-0.2, one MW-CBD but no heat treatment; 1CT-P10-pH6-0.2, one MW-CBD with heat treatment; 2CT-P18-pH6-0.2, two MW-CBD with heat treatment; 3CT-P20-pH6-0.2, three MW-CBD with heat treatment

From diffused reflectance experiments, using Kubelka-Munk procedure, energy bandgap values were obtained from the plot of $[\mathbf{hv} * F(\mathbf{R})]^2 = A(\mathbf{hv} - E_g)$ (see Table 1). Results indicate a direct bandgap as expected for CuO and values agree with those reported for nanostructured CuO (Zhang, et al, 2014).

Number of MW-CBD processes	Sample	Bandgap (eV)	
One, no heat treatment	1ST-P11-pH6-0.2	2.45	
One plus heat treatment	1СТ-Р10-рН6-0.2	2.28	
Two plus heat treatment	2СТ-Р18-рН6-0.2	1.83	
Three plus heat treatment	3СТ-Р20-рН6-0.2	1.53	

Tab. 1: Energy bandgap for films from different number of MW-CBD processes (0.2M Cu(AcO)₂ concentration and pH6)

As observed in Table 1, values increase for samples with a lower number of MW-CBD processes. This is consistent with the presence of quantum size effects due to very fine nanomorphology and it should be studied further with higher resolution scanning electron microscopy (with a higher number of processes nanocrystal size may increase). Nonetheless, the possibility of controlling CuO gap value using MW-CBD is quite interesting for band engineering.

Typical Raman spectra corresponding to films with a different number of processes are shown in figure 5. As can be seen, the characteristic Raman active modes of monoclinic CuO (tenorite) at 296 cm⁻¹ (A_g), 446 cm⁻¹ (B_g ¹) and 631 cm⁻¹ (B_g ²) are present, in accordance with previous reports (Debbichi, et al, 2012). Both Raman active modes only include movement of oxygen anions, with copper cations in almost fixed positions (in A_g mode the anions displace along the (010) direction while in B_g modes the anions displace perpendicular to the (010) direction (Ekuma, et al, 2014).



Fig. 5: Raman spectra for samples with different number of MW-CBD processes: 1ST-P11-pH6-0.2, one MW-CBD but no heat treatment; 1CT-P10-pH6-0.2, one MW-CBD with heat treatment; 2CT-P18-pH6-0.2, two MW-CBD with heat treatment; 3CT-P20-pH6-0.2, three MW-CBD with heat treatment

Only pure CuO is detected as film component. Spectra evolution shows that crystallinity increases with the number of processes since the wider the Raman peaks, the higher the crystal disorder. This is also consistent with an increase of nanocrystal size; the higher this size, the lesser disorder. The wide peak below 600 nm⁻¹ can be associated to the FTO substrate. It decreases as film thickness increases since laser light intensity does not reach the FTO substrate when thicker CuO films absorb it.

Typical XRD patterns corresponding to films with a different number of processes are shown in figure 6. All XRD patterns show mainly FTO substrate diffraction peaks, which match with the PDF 41-1445 of Cassiterite SnO₂. Only XRD patterns corresponding to films with two and three processes show three relatively broad peaks that fairly match the PDF 48-1548 that corresponds to the tenorite CuO phase (monoclinic system). No other copper-based material was detected by XRD.



Fig 6: XRD patterns corresponding to samples with different number of processes: 1ST-P11-pH6-0.2, one MW-CBD but no heat treatment; 1CT-P10-pH6-0.2, one MW-CBD with heat treatment; 2CT-P18-pH6-0.2, two MW-CBD with heat treatment; 3CT-P20-pH6-0.2, three MW-CBD with heat treatment. The insert shows peaks corresponding to CuO.

The insert in figure 6 shows peaks corresponding to CuO. These peaks are at: 32.58°, corresponding to the (110) plane; 35.68°, with contributions from the (002) and (11-1) planes; and 38.88°, resulting from the (111) and (200) planes. Relative intensities of these three peaks are quite close to those of the reference (PDF 48-1548), but their relative intensities do not match that of the rest of the peaks in that reference. For instance, peaks at 48.76°, 61.58°, 66.28° and 68.19° are not present in the XRD pattern in figure 6 but their intensities should be higher than that of the (110) plane. This indicates preferential growth that could be induced by the FTO substrate.

It can also be noted that the peaks present in the patterns of 2CT-P18-pH6-0.2 and 3CT-P20-pH6-0.2 samples are slightly shift to higher diffraction angles, with respect to those of the reference, indicating some degree of lattice parameters contraction. Increase in surface/interface stress due to incomplete atomic coordination in such lattice discontinuities has been identified as the main factor for cell parameter contraction in CuO and other nanostructures (Borgohain et al, 2000).

Figure 7 shows Raman spectra of CuO films fabricated with different pH values of the precursor solutions but equal number of MW-CBD processes and the same concentration of the Cu(AcO)₂ solution. It is important that only with these two pH values, pH6 and pH7, CuO films MW-CBD was possible. For more acidic precursor solutions, films did not deposit and for higher pH values, a precipitate formed in the solution without MW-CBD.



Fig 7: Raman spectra corresponding to films fabricated with precursor solution pH6 and pH7. Both samples, 3CT-P20-pH6-0.2 and 3CT-P40-pH7-0.2, endured three MW-CBD processes with heat treatment. Equal concentration of the Cu(AcO)₂ solution was used.

One can observe that Raman spectra for pH7 are better defined than for pH6. This indicates a higher degree of

crystallinity consistent with larger nanocrystal size. In addition, one can notice different intensity relations between peaks A_g and B_g^{1} . This might be due to preferential growth in a certain nanocrystal direction and it might be observed with higher resolution scanning electron microscopy (Gonzalez, et al, 2020).

Figure 8 shows XRD patterns of CuO films fabricated with different pH values of the precursor solutions but equal number of MW-CBD processes and the same concentration of the Cu(AcO)₂ solution. One can observe that CuO peaks are better defined when using precursor solution with pH7.



Fig 8: XRD patterns corresponding to films fabricated with precursor solution pH6 and pH7. Both samples, 3CT-P20-pH6-0.2 and 3CT-P40-pH7-0.2, endured three MW-CBD processes with heat treat<<ment. Equal concentration of the Cu(AcO)₂ solution was used.

For films in figure 8, it was possible to find crystallite size applying Scherrer analysis to the peak at 32.6° which is produced by diffraction of the (110) plane. This is the only well-resolved peak because only diffraction from one crystal plane contributes. In Table 2 one can observe a smaller value for the full width at half maximum (FWHM) of the sample fabricated with pH7 of the precursor solution; therefore, crystallite size is significantly larger in this case. Larger n<anocrystal size implies higher crystallinity and explains the better definition obtained for XRD patterns (and Raman spectra, as well) when using pH7.

Film	20 (°)	FWHM (°)	D (nm)
3СТ-Р20-рН6-0.2	32.6	0.46	18
3СТ-Р40-рН7-0.2	32.6	0.21	39

Tab. 2: Crystallite size D of films fabricated with precursor solution pH6 and pH7

Figure 9 shows Raman spectra of CuO films fabricated with different concentrations of the $Cu(AcO)_2$ solution but the same number of MW-CBD processes and equal pH value of the precursor solution. Both Raman spectra in figure 9 show characteristic vibrational modes for monoclinic CuO. Only a broad shoulder below the vibrational mode $Bg^{(2)}$ does not correspond to monoclinic CuO. This shoulder could be a contribution from the FTO substrate. Thicker films would make less noticeable this shoulder for samples fabricated with the higher concentration value.



Fig 9: Raman spectra corresponding to films fabricated with different concentrations of the Cu(AcO)₂ solutions. 0.1M and 0.2M. Both samples, 2CT-P44-pH6-0.1 and 2CT-P18-pH6-0.2, endured two MW-CBD processes with heat treatment. Equal pH value of the precursor solution was used.

The better defined Raman peaks for the film fabricated using the $0.2M \text{ Cu}(\text{AcO})_2$ solution indicate increased crystallinity for this concentration value.

Figure 10 shows XRD patterns for samples fabricated with 0.1M and 0.2M Cu(AcO)₂ solution concentrations. Better defined CuO diffraction peaks are observed for films fabricated using 0.2M Cu(AcO)₂ concentration. XRD patterns, as well as Raman spectra, show that higher crystallinity films and/or thicker films are obtained for films fabricated using 0.2M Cu(AcO)₂ solution concentration.



Fig 10: XRD patterns corresponding to films fabricated with different concentrations of the Cu(AcO)₂ solutions, 0.1M and 0.2M. Both samples, 3CT-P51-pH6-0.1 and 3CT-P20-pH6-0.2, endured three MW-CBD processes with heat treatment. Equal pH value of the precursor solution was used.

4. Conclusions

CuO films have been deposited on conducting glass (FTO) by means of a novel liquid phase deposition technique named microwave activated chemical bath deposition (MW-CBD). Different procedure conditions have been used for analysis of this technology when growing CuO films. The number of MW-CBD processes performed for each film studied varies from one to three. The employed precursor solutions have different copper (II) acetate solution concentrations and pH values.

All deposited films show very good adherence to the conducting glass (FTO), with deposition times shorter than 5 minutes and precursor solution temperature below 75 °C. Microwave heating of the conducting substrate during

the process is determinant since it causes an FTO temperature higher than the precursor solution temperature. CuO grows directly on the substrate rather than been deposited from a nucleated precursor solution.

X-ray diffraction and Raman spectroscopy show that only the CuO tenorite phase is present. They all show wide peaks that indicate crystal disorder corresponding to nanostructured morphologies. Film crystallinity improves with the number of processes, higher Cu(AcO)₂ concentration and pH7 of the precursor solution.

Behavior of optical transmission and absorption spectra confirms that film thickness grows for each deposition process.

Kubelka-Munk treatment of diffused reflection spectra show that gap energy decreases with the number of processes indicating quantum size effects. This is consistent with observations from XRD patterns and Raman spectra.

Perspective control of crystallinity (nano-crystal size) and bandgap value with this simple, low cost, MW-CBD technique is of importance for band engineering. This is needed for certain devices, particularly solar cells and water splitting photoelectrodes.

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A Cost-effective Photovoltaic Architecture with Dual Quantum Tunneling in a Monolithic Perovskite/Si Tandem Device

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Abstract

A 2-terminal monolithic tandem photovoltaic architecture was conceptually constructed with both organicinorganic metal halide perovskite upper cell and asymmetric Si-based heterojunction dual carrier's tunneling bottom cell. The interconnection layer of the cells was indium tin oxide (ITO) film of about 80 nm formed by r.f magnetron sputtering deposition of hole selected ultra-thin passivating contact $a-SiO_x(In)$ layer on silicon substrate. At rear side of the Si wafer a wet nitric acid oxidized silicon layer SiO_x (<1.6 nm) and subsequently d.c magnetron sputtered TiN_v coupling layer of SiO_x/TiN_v acted as electron passivated contact. Thus, the quantum tunneling of hole and electron through two kinds of silicon oxides was realized. The analyses of the graded distribution of In, Si and O elements in the interfacial region of ITO/n-Si and amorphous lattice morphology of the ultrathin a-SiO_x(In) layer were gained through the characterizations of X-ray photoemission spectroscopy and high-resolution transmission electron microscope. The intrinsic and p-type conductance of ultrathin SiO_x(In) layer was modeled by molecular dynamics and density function theory. The good photovoltaic feature of the devices has been obtained by current-voltage measurement under AM 1.5G illumination, and its optimized PV character has been simulated by AFORS-HET program. Finally, the Sibased bottom cell was cohered by an efficient n-i-p perovskite cell as a monolithic tandem PV device. The power conversion efficiency of the tandem device has been numerically predicted to be more than 29 % by combining the experimental and simulation data, under the optimized parameters of J_{sc}, V_{oc} and pFF.

Keywords: Tandem cells, photoelectric conversion, SQIS structure, quantum dual tunneling

1. Introduction

Nowadays, the efforts strive to amalgamate the exceptional performance of those organic-inorganic metal halide perovskite solar cells (PSCs) with market-established photovoltaic (PV) technologies such as crystalline silicon (c-Si) solar cells in the form of perovskite/silicon tandems has been mentioned to the agenda of science and technology development (Chen et al. 2019; Jošt et al. 2018; Mazzarella et al. 2019; Nogay et al. 2019; Sahli et al. 2018). Such two-terminal tandems hold the promise to enable a very high-performance PV technology, surpassing single-junction efficiency limits, with high market relevance. Scientifically, in addition to desirable properties such as high absorption coefficient, low Urbach energy, and long charge carrier's diffusion lengths of the perovskite materials, especially, the bandgap can be easily tuned by varying their composition of I/Br ratio. Alongside these properties, the availability of various fabrication techniques that are compatible with deposition on textured c-Si substrates, has been vital toward the development of efficient perovskite/silicon tandem solar cells (Al-Ashouri et al. 2020; Jošt et al. 2020; Roß et al. 2021; Wang et al. 2021). However, the critical challenges that require sustained research efforts are device stability of PSCs architecture, cost-efficient massive-scale processing, and the fulfillment of the perovskite/silicon tandems to yield PCEs well beyond 30%. Fortunately, for the single-junction PSCs, the n-i-p architecture has been most successful to date in terms of device performance, thanks to defect and interface passivation, from which the perovskite-Si tandem research become more beneficial (Liu et al. 2020; Jeong et al. 2021a, 2021b; Zheng et al. 2020). Thus, an effective tandem scheme is present for the n-i-p perovskite / c-Si solar cell and its power conversion efficiency (PCE) has been mainly investigated so far.

In addition, metal halide perovskite solar cells (PSCs) have become the most promising new-generation solar cell technology. To date, perovskites also represent the only polycrystalline thin-film absorber technology that has enabled > 25.5 % efficiency for wide-bandgap solar cells (NREL 2021), making wide-bandgap PSCs uniquely positioned to enable high efficiency and low-cost tandem solar cell technologies by coupling wide bandgap perovskites with low-bandgap absorbers, such as crystalline silicon, CIGS or itself with lower band gaps (Kim et al. 2019; Mazzarella et al. 2019; Nogay et al. 2019; Sahli et al. 2018; Yang et al. 2019).

On the other side, for single-junction solar cells of monocrystalline silicon based material, the ultimate PCE is governed by the Shockley–Queisser theoretical limit (29.43%) (Shockley and Queisser, 1961). The primary

energy loss of a single-junction solar cell includes the unabsorbed long-wavelength photons and thermalization of high-energy photon-generated carriers (Nelson et al. 2013). Nevertheless, the appropriate overlying design may plenarily harness solar energy converting electric power through wide spectroscopic absorption of sun's light, i.e., high-energy photons are absorbed by the upper wide-bandgap subcell, and lower energy photons are absorbed by the bottom narrow-bandgap subcell (Eperon et al. 2017). Of course, the matching of short-circuit current density (mA/cm²) between top and bottom cells should be satisfied for any materials.

Furthermore, in accordance with the PV enhancement principles mentioned above, a realistic option has been proposed for the tandem scheme. As we know, high photoelectric conversion efficiency of crystalline silicon photovoltaic (PV) devices, so far, besides silicon heterojunction (SHJ) and tunneling oxide passivation contact (TOPCon's) types with heterojunction or homojunction, respectively, other types have been developed with improved technologies in time line. But, top cells in this tandem schematic require planar surfaces for fabrication, e.g., due to spin-coated layers, thus need to be in n-i-p configuration. Currently, silicon-based heterojunction solar cells provide more flexibility in this regard and can be used in either polarity. Besides, typical SHJ cells already feature a front transparent conductive oxide (TCO) layer that can serve as the perovskite's bottom contact similarly as in single-junction perovskite solar cells, allowing for relatively simple process integration. Thus, in the past, much greater efforts are devoted to developing tandem cells based on SHJ solar cells. Additionally, the advantage of Si heterojunction cells lies in their very high efficiency, brought about by a very high V_{oc} of 740 mV and a certified efficiency of 26.6% (Yoshikawa et al. 2017). However, this device is fabricated with interdigitated back contacts, not suitable for 2T applications. On the other side, it is difficult to assemble a 2T tandem PV device through perovskite to Si-based TOPCon's cell, in spite of its high PCE.

Recently, we cultivated a simplified process to fabricate a dual tunneling Si-based PV device with indium tin oxide (ITO)/a-SiO_x(In) and SiO_x/TiN_x passivation contact layers for either hole and electron selectivity, respectively (Gao et al. 2017; Song et al. 2018; Wu et al. 2020). On the other hand, its optical and electronic structures on the front surface of the device were suitable for the interconnection to a metal halide perovskite device with a wide-bandgap as top one. Therefore, its potential PV feature could be expectant.

2. Monolithic tandem photovoltaic scheme

2.1 Preparation of SQIS device

2.1.1 Front configuration of SQIS device

In our experiments, the ITO thin films in the range of 80 -120 nm, acting as TCO functional layers possessing idiographic optical and electronic traits for their high transmission in visible region (> 88%) and quite low resistivity (< 0.2 m Ω ·cm), were deposited on chemical polished solar grade n-type CZ silicon (100) wafers (ρ ~1.5 Ω ·cm) and glass-substrates (designated area: 2×2 cm²) by radio frequency (r.f) magnetron sputtering, respectively. The source material was ceramic target of mixing 10 wt. % SnO₂ and 90 wt. % In₂O₃. Before transferring the chamber, the glass-substrates were systematically cleaned in acetone, alcohol, and deionized water for 10 min., and n-Si wafers were cleaned by RCA treatment and immersed in 5 % HF solution for 100 seconds to get rid of native oxide. Prior to each deposition run, the sputtering chamber was evacuated to below 3×10^{-4} Pa. Simultaneously, Ar gas flow of 40 sccm held the gas pressure in the plasma fixed at 1.0 Pa during sputtering to maintain the Si substrate at room temperature. Then, Ag and Al metals were thermally evaporated on the front and rear side of n-Si substrate and subsequently medium temperature alloyed to form electrodes. Thus, a simplified crystalline silicon based optoelectric device was yielded with asymmetric structure and heterojunction style.

In order to gain the microstructure (chemical configuration and physical phase) of the intermediate zone of ITO-Si, the electronic states, and elemental ratio profiling and chemical components of ITO/c-Si interface region was analyzed by X-ray photoemission spectroscopy (XPS) with depth etching. The result was shown in Fig.1a, in which an ultra-thin amorphous silicon oxide layer $(a-SiO_x)$ including indium (In) was synthesized by a solid-phase reaction during the sputtered-induced ITO components absorbed on n-Si substrate to form Si-O or Si-O-In bonds, of which the atomistic configuration and interfacial density of state (DOS) was studied in our previous report by molecular dynamics (MD) and density function theory (DFT) calculation (Wan et al. 2017). The amorphous lattice morphology of the ultrathin a-SiO_x(In) layer and its rough thickness (< 2.0 nm)

was characterized by high-resolution transmission electron microscope (HR-TEM) as manifested in Fig.1b, in which the indium element was included in the ultrathin a-SiO_x(In) layer (1.4-1.6 nm) and acted as an accepted impurity. X-ray source used for XPS (Thermo fisher, Escalab 250Xi) analyses was Al Ka (~1486.6 eV), where the work function of ITO films in the scope of 4.90 - 5.06 eV was also evaluated by ultra-photoemission spectroscopy (UPS) excited through He I line (~21.22 eV) (Gao et al. 2017). The forward sputtering power dependent variation of O/Si ratio and silicon suboxide compositions at etching time of 960 s were shown in Fig.2. A mathematical deconvolution analysis has been carried out for the Si 2p states in Si₂O, SiO, Si₂O₃, SiO₂ as well as Si 2p_{3/2} or Si 2p_{1/2} components, depending on the typical binding energy values (Dreiner et al. 2001).

Accordingly, the delocalized electronic states at $E_v + 0.3$ eV and p-type conductivity near n-Si surface has been induced by the combination of indium (In) element with oxygen and silicon within the interfacial region of ITO film and n-Si substrate (Wan et al. 2017), supporting by numerical calculation of partial and total density of state (DOS) of a-SiO_x(In) layer and DFT as well. Thus, the transport modes of photo-generated hole through the a-SiO_x(In) layer by the ways of tunneling, assisted-tunneling, recombination or diffusion become possible in the present situation.



Fig.1 (a) Atomic percentage of elements in the ITO/n-Si interface region varied with etching time by XPS, including the In, Sn, O and Si elements, also SiO_x oxide; (b) Microscope of intermediate layer a-SiO_x(In) by HR-TEM.



Fig.2 Detailed peak-peak fitting of Si 2p spectra at the etching time of 960s for 80, 120 and 140 W, and the relative proportion of O/Si in amorphous a-SiO_x(In) layer, respectively.

Subsequently, the typical thickness of 80 nm ITO film was deposited on Si substrate by varying sputtering power from 80 to 140 W. Then, Ag and Al metals were alloyed contact by vacuum thermal evaporation, respectively, as front and rear electrodes and the Ag/ITO/a-SiO_x/n-Si/Al device was constructed. Mobility of the ITO film was measured by a four-point probe Hall system (HL5500-PC). The characteristics on short-circuit current density (J_{sc}) to open-circuit voltage (V_{oc}) of ITO/a-SiO_x/n-Si heterojunction PV devices (Named as SQIS) were measured though one-sun's solar simulator system (Sciencetech, SS-150-A). By measuring the lifetime of minority carriers, it is possible to evaluate the effect of different surface treatment processing on surface passivation. Since the front and back surfaces of SQIS heterojunction solar cells were asymmetric, we used the same process to sputter ITO films on the front and back surfaces of silicon. The mode of minority carrier lifetime tester used in our laboratory was WT2000 of Semilab Co. The approach can be referred to

Gao's report in 2017.

Concerning on the photon-generated current associated with the carrier transport through the heterojunction of SQIS device, the obtained larger J_{sc} means that the main contribution arises from minority carrier (hole) near the inversion layer of n-Si absorber. However, the a-SiO_x(In) layer offers a high potential barrier prevent the carriers from the diffusion and shift moving to the end. Hence, a quantum tunneling is quoted to explain the transport behavior. For the electrons in n-Si side, although the effective interaction from both the built-in-potential in inversion layer and a little recombination through the interface states are present, the most of electron might transfer to the end as a negative charge accumulation. On the other hand, the hole induced by photon-excited and near the interface of n-Si side has to tunnel through the high barrier of SiO_x layer. Thus, the accumulation of holes on the opposite end, in virtue of the characteristic of ITO as double performances of semiconductor and quasi-metal, is the proof by the measurable V_{oc} . Basing on the above-mentioned picture, the schematic energy band diagram of ITO/SiO_x/n-Si, at short-circuit condition and under illumination case, is here shown in Fig.3 (a).

We are successful at last making an ideal opto-electric diode with PV characteristic, where the functions of passivation and tunneling are achieved at the same time. Actually, the implement has been done without any premeditation for the solution of our difficulty. The prototype concerning about ITO/a-SiO_x(In)/n-Si heterojunction photovoltaic device is simply fabricated by r.f magnetron sputtering of ITO on n-Si substrate at 150°C. Its J-V relationship is depicted in Fig. 3 (b), and the excellent rectifying characteristic (the saturation dark current density (J₀) can reach to 10^{-7} mA/cm²) of the device is realized under dark J-V as well as the typical photovoltaic (PV) peculiarity of the device is obtained under AM 1.5G illumination (100 mW/cm²). The power conversion efficiency (η) of the device is measured to be 11.47 %, together with open-circuit voltage (V_{oc}) of 0.49 V, short-circuit current density (J_{sc}) of 30.33 mA/cm² and fill factor (FF) of 77.15 %, without surface textured and extra back passivation treatment.



Fig.3 (a) Energy band of ITO / a-SiO_x (In) / n-Si device under one-sun illumination; (b) J-V curve of SQIS device under dark and light conditions, in addition the photovoltaic conversion parameters in AM 1.5 G illumination.

2.1.2 Rear passivation contact stacks of SQIS device (modified)

In this section, the extra passivation contact for SQIS device was replaced by SiO_x/TiN_y (where 0 < x < 2; 0 < y < 1) for Al-BSF. The cross-section of a modified SQIS was illustrated in Fig.4a, in which the ultrathin silicon oxide SiO_x (< 2 nm) was made through the formal nitric acid oxidation of silicon (NAOS) (Kobayashi et al. 2010) process and subsequently reactive magnetron sputtering method was used to lay titanium nitride film at room temperature. The detail experimental processing for fabricate ITO/a-SiO_x(In) composited film on n-Si by r.f magnetron sputtering can be inferred to our previous report (Du et al. 2015). The individual thickness of thin film materials in Fig.4a is also indicated. The quality of the rear SiO_x has been characterized by XPS as shown in Fig.4b, where a nearly stoichiometric SiO₂ is formed on monocrystalline n-Si substrate by the approach. Thus, it means that the chemical passivation of Si surface and the decline of interface state density of n-Si/SiO_x can be expected. When the numerical calculation is deployed to the optimized modified SQIS device, including surface textured and further rear passivation contact by SiO_x/TiN_y coupling layers, the performance of the PV device has been improved so much, and the detail results are given in the following subsections. Thus, the transport of photo-generated electron through the barrier of n-Si/SiO₂-TiN_y can be

interpreted by quantum tunneling besides other mechanisms.



Fig.4 a) Schematic diagram of modified SQIS device; b) XPS of SiO_x/n-Si on rear surface.

2.1.3 Numerical simulation by AFORS-HET for both SQIS and modified-SQIS devices

Considering the structure of the device, the $ITO/a-SiO_x(In)/n-Si/SiO_x/TiN_y$ is similar to that of the SHJ heterojunction device, which is often simulated by using AFORS-HET software of version 2.5. Therefore, we first simulate the photovoltaic performance of the SQIS, in which the material and interface of each layer was set as:

(1) Taking into account the orbital energy level induced by oxygen vacancies and indium element, we put dual effects with passivation and tunneling;

(2) The a-SiO_x (In) is divided into two layers for simulation, including the p-a-SiO_x (In) layer with negative charge center and the intrinsic passivation layer, i-a-SiO_x (In);

(3) The defect arisen from dangling bonds is set to be three types, namely Condce Tail, Valence Tail and Gauss, and the interface state density between i-a-SiO_x (In) and n-Si is $1.0 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$, which refers to ref. (Wu et al. 2020);

(4) According to the literature, the band gap of the p-a-SiO_x (In) layer is set to be 2.06 eV, and the negative charge center concentration is 1 x 10^{17} cm⁻³;

(5) The ITO/p-a-SiO_x (In) interface is set to be Schottky contact, and both the ITO and TiN films are Ohm contact with the front and back electrodes, respectively.

Thus, the parameter settings of each layer and interface are listed in Table 1, while the other parameters are set to be the default values. On this basis, a SiO_x/TiN_y composite layer is arranged on the back of n-Si to simulate the photovoltaic performance of ITO/a-SiO_x(In)/n-Si/SiO_x/TiN_y device.

The photovoltaic performance of ITO/a-SiO_x(In)/n-Si and ITO/a-SiO_x(In)/n-Si/SiO_x/TiN_y heterojunction devices is simulated under the standard sunlight of AM 1.5G, and the result of its J-V curve is shown in Fig.5a. The open-circuit voltage of 0.58 V, short-circuit current density of 37.00 mA/cm², fill factor of 75.90 %, and conversion efficiency of 16.29 % are obtained, which are obviously better than that of experimental results of SQIS device ($V_{oc} = 0.48$ V, $J_{sc} = 2.9.93$ mA/cm², FF = 6.9.90 %). As a SiO_x/TiN_y composite layer stacked on the back, the open-circuit voltage is increased by 0.13 V and finally obtains a high open-circuit voltage of 0.71 V, where the interface state density between n-Si and SiO_x layer is set to be 1.0 x 10¹¹ cm⁻²eV⁻¹. At the same time, there is a significant increase in each photovoltaic parameter, with a short-circuit current density of 40.05 mA/cm², a fill factor of 81.19 % and a conversion efficiency of 23.08 %.

It can be concluded that the optical and electrical gain from back passivation has extra contribution to the conversion efficiency of the device by 7.6 % and 18.3 %, respectively. We believe that the optical gain mainly depends on the absorption and reflection of near-infrared and mid-infrared light by the TiN_y film, because the silicon material is transparent loss to infrared light, accounting for about 42 % of the sun's light.

When simulated with AFORS-HET software, the applied electronic concentration of the composite SiO_x/TiN_y film material is set to be in the range of $10^{21}-10^{22}$ cm⁻³ for the best performance of the heterojunction device. Furthermore, the energy band structure of the SQIS device with multi-interface layer is shown in Fig.5b. It is found that the energy bending of the structure is about 0.92 eV, of which 0.75 eV is on the side of the ITO film

and 0.17 eV on the side of the ultrathin silicon oxide layer, so the larger bending can result in high open voltage. Referring to the previous report (Song et al. 2018), it is indicated that the energy band of the SQIS device was curved to 0.66 eV, while the energy band of the SQIS device with 5 nm n⁺ - a-Si layer was bent to 0.87 eV, of which 0.73 eV was on the side of the ITO film and 0.14 eV on the side of the n⁺ - a-Si film.

Tab.1: List of main simulation parameters of AFORS-HE1 for modified SQIS device				
Parameters	p-a-SiO _x (In)	i-a-SiO _x (In)	SiO _x /TiN*	n-Si
Layer thickness (cm)	1.2×10-7	2×10 ⁻⁸	3×10-5	1.5×10 ⁻²
Dielectric constant	9	9	3.5	11.9
Electronic affinity (eV)	3.5	3.5	4.15	4.05
Mobility gap (eV)	2.06	2.06	3.40	1.12
Optical gap (eV)	2.06	2.06	3.40	1.12
Effective DOS in CB (cm ⁻³)	2×10^{20}	2×10 ²⁰	6×10 ²¹	2.84×10 ¹⁹
Effective DOS in VB (cm ⁻³)	2×10^{20}	2×10^{20}	1×10 ²¹	2.68×10 ¹⁹
Donor doping (cm ⁻³)	-	-	10 ²¹ -10 ²²	2×10 ¹⁵
Acceptor doping (cm ⁻³)	1×10 ¹⁷	-	-	-
Electron (hole) mobility (cm ² /Vs)	40(5)	40(5)	-	1321 (461)

Tab.1: List of main simulation parameters of AFORS-HET for modified SQIS device

Note: The thickness of the silicon oxide layer in the SiOx/TiN composite film is about 1.5 nm, and the TiN film is about 300 nm, hence having a high donor concentration.



Fig.5 a) J-V curves of both ITO/a-SiOx/n-Si with and without extra SiO₂/TiNx; b) the variation of energy band vs thickness into modified-SQIS device, and special on rear passivation.

2.2 Selection of wide bandgap n-i-p perovskite PSCs as top cell

In the two-terminal monolithic tandem PV cells with 2 Shockley–Queisser limit junctions (2-SQJs), an optical bandgap of 1.75 eV is desirous for the top cell, when the bottom cell is c-Si absorber having the bandgap of 1.12 eV. Therefore, a well fabricated metal halide perovskite solar cell (PSCs) with a composition of $C_{S0.12}MA_{0.05}FA_{0.83}Pb$ ($I_{0.6}Br_{0.4}$)₃ (Tan et al. 2018) has been selected as top cell in our optimized 2-SQJs PV system. Through incorporating 5% MA substituting partial Cs element in the previous composition of $C_{S0.17}FA_{0.83}Pb$ ($I_{0.6}Br_{0.4}$)₃, so that its bandgap is still kept as same as a near-ideal bandgap of 1.74 eV (McMeekin et al. 2016). Furthermore, in the experiments, there is almost no hysteretic behaviors in short-circuit current density to open-circuit voltage (J-V) measurements, particularly, FF exceeds 80% and V_{oc} reaches to 1.25 V after the incorporation of a small amount of MA. Consequently, the stabilized PCE of 19.1% with dipolar MA cation in the device architecture of ITO/TiO₂–Cl/perovskite/Spiro-OMeTAD/Au is achieved on planar ITO substrate, where a thick perovskite layer of about 600 nm and an area of 1.1 cm² are validated for our modified c-Si SQIS case.

3. Prediction of conversion efficiency of the tandem system

The prediction of the PCE of the planar n-i-p perovskite/SQIS with stacked passivating contact and interconnection transport layers mainly obeys the following three principles:

1) For the entire stack device, silicon-based short circuit current density loses nearly half in that the EQE response by current matching of two cells;

2) Due to the decrease of short circuit current density and the recombination of interconnection layer, the open circuit voltage has a little lost;

3) Fill factor uses the comparison of the simulation results and the empirical formula.

3.1 Short-circuit current J_{sc}:

The relationship between short circuit current density and external quantum efficiency can be expressed as formula

$$J_{sc} = q \int F(\lambda) IQE(\lambda) [1 - R(\lambda)] d\lambda = q \int F(\lambda) EQE(\lambda) d\lambda$$
 (eq. 1)

Where IQE (λ) [1-R (λ)] = EQE (λ), R (λ) is reflectivity, EQE (λ) and IQE (λ) are external quantum efficiency and internal quantum efficiency, respectively, F (λ) is the density of incident photon flow, q is the elemental charge. Metal halogen perovskite and silicon-based subcells can have good current matching by adjusting the thickness of the interconnection layer and the band gap of PSCs, so that the J_{sc} of tandem cells is considered half of the J_{sc} of silicon-based cell.

So that a value of about 20.0 mA/cm² has been taken as the short-circuit current density of the monolithic twoterminal tandem PV device. Nevertheless, in the calculation, we have to take the J_{sc} value of metal halide perovskite cell if the J_{sc} value of perovskite is less than half of bottom cell, owing to the current matching requirement.

3.2 Open-circuit voltage Voc:

Open-circuit voltage V_{oc} of the tandem cells is conceptually the sum of the two subcell's. However, due to the loss of short circuit current density from top perovskite cell shelter, the V_{oc} of silicon-based bottom cell must has a deficit, thus, the total open circuit voltage is calculated as:

 $V_{oc, tandem} = V_{oc, top} + V_{oc, bottom} + \Delta V_{oc}$ (eq. 2)

Where $V_{oc, top}$ is open-circuit voltage of top cell, $V_{oc, bottom}$ is that of bottom cell, while ΔV_{oc} is a deficit arisen from the decrease of short-circuit current density and a recombination cause of electron and hole in the interconnection layers of the both cells. The reasons for ΔV_{oc} mainly come from two aspects:

(i) Deficiency from short-circuit current density: The ΔV_{oc} of the subcells in the tandem is estimated by the logarithmic dependence of ΔV_{oc} on the photocurrent density (Wurfel et al. 2015). The deficit of open-circuit voltage (ΔV_{oc}) about the SQIS device in this part is:

$$\Delta \text{Voc} = \frac{k_B T}{e} \left[ln \left(\frac{J_{sc,before} + J_0}{J_{sc,after} + J_0} \right) \right]$$
(eq. 3)

Where k_B is Boltzmann constant, T is absolute temperature; J_0 is a recombination current density. Since the order of magnitude of J_0 in both cells is a few tens of fA/cm² at most, and the order of magnitude of J_{sc} in both cells is in the level of mA/cm², so that J_0 can be ignored. Thus, if $J_{sc,before} = 40.05 \text{ mA/cm}^2$, or $J_{sc,after} = 20.00 \text{ mA/cm}^2$, it can be derived that the ΔV_{oc} is about 18.05 mV in terms of eq.3. Nevertheless, for upper perovskite cell, the short circuit current density decreases slightly, hence the deficit of open-circuit voltage is negligible.

(ii) Deficit from interconnection layer: The intermediate layer for connecting two subcells inevitably produces a lower carrier recombination rate, resulting in the accumulation of electrons from perovskite cell and holes from silicon-based cell in the intermediate layer (Campbell et al. 1986). It has been estimated for a tandem system that about 20 mV of ΔV_{oc} is lost mainly due to the electrical loss at the recombination layer (Liu et al. 2015). Thus, the total loss of open-circuit voltage ΔV_{oc} is about 38.05 mV, combined with the loss of open-circuit voltage caused by halving the short-circuit current density mentioned above. It is derived that the open-circuit voltage of planar n-i-p perovskite/SQIS tandem cells with SiO_x-TiN_y rear contact can reach about 1.92 V.

3.3 Filled factor pFF

Ideally, pFF is just a function of open circuit voltage. Owing to the fill factor of any solar cell is dependent on the ratio of carrier's transport velocity to recombination velocity, so do the tandem cells. Therefore, the fill factor of the tandem cells should be dominantly determined by the modified SQIS cell, additionally, the following approximate empirical eq.4 could be deployed to estimate the pseudo-fill factor (pFF), because it is only a function of open circuit voltage (V_{oc}) under ideal conditions and without parasitic shunt resistance (Campbell et al. 1986; Meng et al. 2018).

$$pFF = [\upsilon - \ln(\upsilon + 0.72)]/(\upsilon + 1)$$

(eq. 4)

Where v is the normalized open circuit voltage, given by $v = \frac{q V_{oc}}{n K_B T}$, where q is electron charge, while n is the ideal factor of a diode and in the range of 1-2. Generally, the pFF value is in the range of 75.6 % - 85.1 % for a tandem cells, dependent on the quality of the cells, but in our case, the optimized value of pFF is estimated to be about 81.19 % for the modified SQIS device.

3.4 Power conversion efficiency η

r

The conversion efficiency of the tandem cells can also be calculated by the equation 5 as

$$\eta = (J_{sc}V_{oc}FF/P_{in}) \times 100\%$$
 (eq. 5)

Thus, the results of J_{sc} , V_{oc} , pFF and efficiency η are summarized in table 2 for the individual and tandem cells.

Tab. 2: The photoelectric parameter	rs acquired by experimental	l and numerical calculation
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Framework of device	Voc (V)	J _{sc} (mA/cm ²)	FF (%)	η (%)
Modified-SQIS	0.710	40.05	81.19	23.08
Planar n-i-p perovskite $(E_g=1.74 \text{ eV})^{[28]}$	1.25	19.00	81.50	19.10
Planar n-i-p perovskite/SQIS with rear SiO _x /TiN _y	1.92	19.00	81.19	29.62

4. Conclusion

In this investigation, we re-design and prepare new monolithic tandem solar cells through a combination of modified SQIS as bottom cell with n-i-p perovskite as top cell, basing on the concept of spectral response and current matching for both subcells. It is found that the modified SQIS is a good candidate as bottom cell for the tandem system, because the enhancement of near-infrared response (EQE) of the ITO/a-SiO_x (In)/n-Si/SiO_x-TiN heterojunction device with double-tunneling features has been verified by a series of experiments and simulations. In particular, both double layer's composite film materials of ITO/a-SiO_x(In) and SiO_x-TiN are most significant for the built-in potential, carrier's selectivity, passivating contact and quantum transport of the asymmetric PV device, in which the microstructure, chemical configuration and passivation behavior of the front a-SiO_x(In) and rear SiO_x on silicon substrate are totally different, because the negative charge contained in a-SiO_x(In) and positive charge in SiO_x for the field passivation effects of hole and electron are their distinct traits, respectively. On the other side, the higher electron concentration (10^{21} - 10^{22} /cm³) in ITO or TiN films obtained by Hall measurements has manifested that both the films are degenerated materials, such as heavy doped semiconductor or quasi-metals, in that the equivalent Fermi level of a-SiO_x (In) or TiN is localized near to the valence- or conduction bands of n-Si, respectively, benefit to the built-in potential and extraction of photon-generated carriers.

Additionally, the change or increment of electron concentration n_e in TiN_x film is ascribed to a small deficit of nitrogen element during reactive magnetron sputtering process by XPS characterization, and an energy band bending from accumulation, flat and reversion near interface of n-Si/SiO_x-TiN has been gained by the calculation of the shift of conduction band edge in terms of the variation of electron concentration n_e of TiN_x by means of AFORS-HET program. It is also found that the increase in photocurrent density is mainly due to

the increase of EQE near-infrared region, while the decrease in dark current is owing to the reduction of carrier's recombination arisen from the valence band offset between n-Si and TiN_x (2.30 eV), furthermore, the change of electronic barrier at the n-Si/SiO_x-TiN interface is controlled by the n_e of TiN films. Thus, SiO_x-TiN back contact to n-Si plays the multi-roles of interface passivation, electron export, and hole blocking, leading to the increases of open-circuit voltage, short-circuit current, fill factor as well as PCE of the modified SQIS device. So that, a boost increase of the PCE has been obtained in the estimation, which is more than 23.0 %. Moreover, a higher prospective conversion efficiency of 29.0 % for the planar n-i-p perovskite/SQIS with SiO_x-TiN tandem cells has been predicted through an available estimation on the maximum values of J_{sc} , V_{oc} and pFF, mentioned in section 3 and table 2, where the photovoltaic parameters of both perovskite and n-Si based devices are taken from reference [28] and optimized SQIS by means of the state of the art fabrication and numerical simulation. The near-infrared response and enhancement of EQE after SiO_x-TiN back contact to Si-based SQIS device is crucial for improving the performance of modified SQIS and tandem cells as well.

Moreover, there are three key points to successfully realize in the monolithic tandem photovoltaic device: first, the rational design and preparation of silicon-based SQIS device; second, the band gap of halogen perovskite is more than 1.74 eV; third, the intermediate electron - hole recombination layer and other auxiliary thin film materials are preferred. Thus, the requirements of the photovoltaic device principle and the goal of low cost and high efficiency can be achieved.

5. Acknowledgements

This work is mainly supported by the National Natural Science Foundation of China (No. 61874070, 61674099 and 61274067) and the R&D Foundation of the SHU-SOENs PV Joint Laboratory (No. SSE0700601).

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D-01. Agri Photovoltaics
The Effect of Surface Cover Vegetation on the Microclimate and Power Output of a Solar Photovoltaic Farm in the Desert

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Abstract

Part of a commercial solar photovoltaic farm in the hot dry Negev Desert of Israel was modified by planting lowrise surface cover crops in the spaces between the rows and beneath the solar panels. In two test plots of about 0.22 hectares each, modifications to the microclimate resulted in lower air temperature, higher humidity and reduced radiant loads on the lower face of the panels compared to a control plot that was not modified. PV panel temperature in the planted test plots was up to 4.5°C lower, resulting in an increase of electricity output of 1.2% over the summer. Water consumption for irrigation was 24-30% lower in the partly shaded zones during the initial planting and growth phase (depending on the type of crop), but differences in the height of summer, once the crops had matured, was only 7-11% lower. The crop yields beneath a partly shaded area beneath the panels were about 60% of the yield in fully exposed areas of the site, but the Land Equivalent Ratio of the test plots was 1.67. An analytical model, adapted from the Faiman equation, can describe PV panel temperatures in the presence of crops accurately, providing a basis for estimating the electricity output based on their rated temperature coefficient.

Keywords: PV panel temperature, desert, pilot study, field experiment, Land Equivalent Ratio

1. Introduction

Agrivoltaic systems promise greater benefits from a limited site area (Dupraz et al, 2011), reflected in a Land Equivalent Ratio > 1, through dual use of the same plot for electricity generation and crop cultivation. Simulations show that there are trade-offs between higher density of solar panels and greater crop production in mono-facial panels (Dinesh and Pearce, 2016), as well as in bi-facial ones (Sun et al, 2018). Solar farms are known to generate a localized daytime heat island (Broadbent et al, 2019), which should lead to a reduction in the power output of the panels. Meanwhile, studies of rooftop PV have explored synergies between solar panels and a green roof, indicating that the presence of plants may lead to an increase in electricity output of approximately 1% relative to a non-planted roof (Ogaili and Sailor, 2016).

The objectives of the present study were to deploy a pilot study in an operational commercial solar farm to establish the magnitude of the electricity output premium; to monitor the microclimatic effects of vegetation in a full-scale solar farm; to assess the effects of panel shading on crops in a hot dry climate; and to describe the practical difficulties of retrofitting an existing solar farm through the addition of agriculture.

2. Methods

Two test plots of about 45x50 meters each in a commercial solar PV farm with mono-facial panels were modified by the addition of crops planted both beneath the panels and in the spaces between rows (Fig. 1, left). The electricity production from the test plots was compared to the output of an otherwise identical control plot that did not receive any treatment. The solar farm is located in Israel's Negev Desert, 31.01N 34.76E. The climate is characterized by sunny, dry summers with a mean daily maximum temperature (July) of about 34°C and mild winters with mean daily max (January) of about 19°C. Annual global horizontal solar radiation averages 2,365 kWh m⁻². Annual rainfall averages 105mm, with no rain occurring between May-September.

The crops planted in both test plots were low-rise plants selected for their quick growth, low height and ability to create a complete cover of the surface: Dichondra repens and Viola hederacea in one plot and Pelargonium graveolens in the other. Planting was initiated in spring (April 2020) and full vegetated cover was achieved by June (Fig. 1, right). Measurements were then carried out continuously throughout the summer and autumn of 2020 and the winter of 2021.

An extensive monitoring infrastructure was installed to measure micro-meteorological variables including air temperature, humidity, wind speed and direction, and solar radiation for the site as a whole (Tab. 1). At each of the three plots, electric power, voltage and current were recorded, and measurements were made of temperature, humidity, and net all-wave radiation. The temperature of the solar panels was measured at 3 heights above the ground in each plot. Data were recorded on a Campbell CR1000 at 10-minute intervals.



Fig. 1: Left - aerial view of solar farm showing location of test plots. Right - Pelargonium in one of the test plots.

instrument	parameter	location
T-type thermocouples	panel temperature	panels
Campbell hygrovue5	air temperature, relative humidity	under the panels
Apogee net radiometer	net all-wave radiation	under the panels
CR Magnetics CR5210	electric current	panels
Phoenix Contact SCK-M-I-8S-20A	electric voltage	panels
GMX500	air temperature, relative humidity, wind speed and direction	edge of solar farm
Kipp & Zonen CMP3	global solar radiation	edge of solar farm

Tab. 1: Measurement instruments and locations

3. Results

3.1 Microclimate modification

Compared to the control plot, air temperature in both test plots was lower than air temperature in the control plot (Fig. 2, left). The difference was minimal at night and reached a maximum of about 1.4K in the early afternoon. Although we did not perform a complete energy balance for the three test plots, the temperature reduction is attributed to evapotranspiration from the crops: The decrease in air temperature in the test plots is mirrored by an increase in the moisture content of the air, as indicated by the relative humidity (Fig. 2, right). This difference was greatest in the morning hours and declined gradually in the afternoon.



Fig. 2: Left – Average diurnal profile of the difference in air temperature between the control plot and test plots. Right - Average diurnal profile of the difference in relative humidity between the control plot and test plots, for the month of August 2020.

3.2 Panel temperature

PV panel temperature in the test plots was significantly lower than in the control plot during daytime, but nearly the same at night. The difference was substantially greater in the top row of panels than in the lower rows (Fig. 3): the lower face of these panels was exposed to less reflected solar radiation due from the plants (albedo 0.20-0.22) than from exposed desert soil (albedo 0.35) and to less IR radiation from the cooler vegetation. Panels in the lower part of each row were in deep shade and had a similar radiant balance in all test plots.



Fig. 3: The diurnal pattern of the difference in panel temperature between control plot and Dichondra test plot at 3 different heights above the ground, for the month of August 2020.

3.2 Power output

The electricity output of panels in the test plots was compared to the output of a similar string of panels in the control plot at three heights above the surface. To reduce potential error from differences among individual panels, output was measured for strings of 10 panels. The increase averaged 0.7% in the lowest row of panels (about 1 meter above the surface) and 1.2% at the upper row (about 2.5 meters above it). The measured improvement is consistent with output corrected for panel temperature using the manufacturer's temperature coefficient (-0.41% / K).



Fig. 4: The diurnal pattern of differences in power output between the Dichondra test plot and the control (average for July 2020). Note the difference between values for the upper row of panels only (HI) and the average for the entire plot (AVG).

3.4 Irrigation requirements

To support crop growth in this climate, irrigation is required. Water supply was metered separately for each zone in the test plots to assess the effect of shading on evapotranspiration (Fig. 5). During the initial establishment phase (in spring), Dichondra plants in the sun required an average of 94.2 m³ per day per hectare, and plants in the shade beneath the panels required 71.3 m³ per day per hectare, a reduction of 24%, while Pelargonium plants required 54 m³ per day per hectare in the sun and 37.8 m³ per day per hectare beneath the panels, a reduction of 30%. The corresponding figures for the summer period (June 26 – September 29), once the plants had matured, were 46.2 and 41.0 m³ per day per hectare (Dichondra) and 37.3 vs. 34.8 m³ per day per hectare (Pelargonium), so that differences dropped to only 11.3% and 6.7%, respectively.



Fig. 5: Irrigation supplied to the test plots, accounting for season and exposure to sun.

3.4 Effect on crop growth

Plant growth was assessed by two metrics: plant morphology and crop biomass. The Pelargonium plants growing in partial shade beneath the PV panels reached an average height of 64 cm, compared to only 42 cm in the space between rows of panels, and had substantially larger leaves which were a deeper green in color (Fig. 6). However, the biomass harvested at the end of August from the sunny area was equivalent to 51 tons per hectare, compared to 38 tons in the semi-shaded area below the upper rows of the PV array and only 23 tons beneath the lowest rows, where plants were in deep shade.



Fig. 6: Pelargonium leaves from plants growing in partial shade (left) and full sunlight (right).

4. Analysis and discussion

A key to increasing electricity output of PV panels is lowering their temperature. A widely used correlation for estimating panel temperature T_m in different environmental conditions (Faiman, 2008), which was derived from empirical data at a desert test site in Israel, is given in Eq. 1,

$$T_m = T_a + \frac{E}{U_0 + U_1 \times W} \tag{eq.1}$$

where T_a is air temperature [°C], E is incident solar radiation [W m⁻²], W is wind speed (m s⁻¹] and U_0 and U_1 are empirical constants equal to 6.85 and 25, respectively.

The Faiman correlation is very simple, and despite limited inputs it is quite robust. However, it does not support description of the effect of differences in ground cover that affect the absorption of radiation and wind speed adjacent to the panel. To address this limitation while retaining the simplicity of the original formulation, a small modification is proposed, based on empirical data from the present study:

$$T_m = T_a + \frac{aE}{U_0 + U_1 \times W} \tag{eq.2}$$

where α is panel absorptivity and the constants U_0 and U_1 are equal to 6.85 and 18, respectively. α is 0.91 for a panel above a planted surface, and 0.95 for a panel above a light-coloured desert soil, to account for greater reflection due to the higher surface albedo and the increase in the incident flux on the lower face. Correlations between measured and modelled panel temperature for the daylight hours (6:00-18:00) on a representative summer day showed excellent agreement for both types of surface cover (y=0.9929x, R²=0.9976, RMSE=2.35K for the control plot; y=1.0036x, R²=0.9977, RMSE=2.22K for the Pelargonium plot).



Fig. 7: Correlation between measured panel temperature in the Pelargonium test plot and temperature modelled using the revised Faiman model (left) and the control plot (right). Data for June 27, 2020.

Although not recorded quantitatively, visual inspection also showed that vegetation reduced exposure to airborne dust. This effect will be monitored accurately in future experiments.

5. Conclusions

The pilot study demonstrated that existing solar farms may be modified to allow dual use of the land to grow crops. In an installation with mono-facial panels designed *a priori* to optimize solar PV output, the presence of vegetation resulted in a modest increase of electricity output. The overall LER for the test plots was 1.67, but the economics of dual-use farms depends on the value of the crops grown and the cost of production, especially irrigation. Research is required to establish the most suitable crops for such installations and to optimize irrigation.

6. Acknowledgments

The experiment was made possible thanks to funding by the Israel Electric Corporation and the cooperation of EDF-Renewables.

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D-02. Floating Photovoltaics

Large Scale Floating Photovoltaics on Lake Nasser for Effective Power Production and Reducing Water Losses

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Abstract

Lake Nasser is one of the world's largest artificial lakes. It is an important driver of Egypt's economy, and it is the base for increasing agricultural land use in the country. However, being located in one of the most arid regions the reservoir is experiencing strong water losses due to evaporation. With growing population, water and power demand are further rising, and are becoming a major concern for the Egyptian people. Floating photovoltaic systems are a mitigation to strong water evaporation, while simultaneously effectively producing power. This concept study identifies a site in the northwestern part of Lake Nasser. In this calm part of the reservoir around 56 km² might be suitable for installing FPV systems. Although this would be a very huge FPV field it only would cover around 1% of the Lake's surface. Various state-of-the-art floating PV structures have been analyzed. The maximum achievable installed power is 10.2 GW_p and would lead to an annual power production of approximately 21 TWh. Due to directly hindering evaporation, where floaters are covering the surface, combined with the evaporation leverage effect by cooling also surrounding water the annual evaporation reduction is estimated to reach a maximum of approximately 0.177 km³.

Keywords: Floating photovoltaic systems, cooling effect, evaporation reduction, FPV hydro power synergy

1. Introduction

According to (FAO, 2016) Egypt is expected to meet the threshold for absolute water scarcity by 2030. Egypt's dominant water source is the Nile River. Since the filling of the Grand Ethiopian Renaissance Dam in Ethiopia started the Nile is experiencing an estimated yearly shortage of 13.5 km³. This shortage of water has been rising tensions between Egypt, Sudan and Ethiopia. In addition, similarly to other countries on the African continent, Egypt has been affected by climate change, facing severe droughts that have had direct repercussions on water availability.

In southern Egypt a significant amount of water is lost due to the high evaporation rates of the Aswan High Dam Reservoir (AHDR). The huge Egyptian partition of the AHDR is called Lake Nasser. It forms one of the world's largest artificial lakes with a surface area of around 5,250 km². El-Shazli *et al.*, 2018 estimated a long-term annual evaporation loss of 2,007 mm averaged over the entire reservoir. This results in annual evaporation losses of 10.5 km³. Due to climate change with rising temperatures and predicted harsher droughts, the evaporation rate -which is already among the highest in the world- is expected to increase further. Hence, the evaporation of Lake Nasser is regarded as a serious problem.

A second concern is Egypt's population growth. Together with further industrialization, a strongly rising electricity and water demand is expected. To meet such increasing energy demand, the government's Integrated Sustainable Energy Strategy has set renewable energy targets of 42% by 2035.

A solution to address both major issues is the use of floating solar photovoltaic panels (FPV) on Lake Nasser. Egypt is characterized by having a high solar resource potential, with an average of Global Horizontal Irradiance of 6.3 kWh/m² per day or 2285 kWh/m² per year. Due to low latitude and absent of rainy periods this remains relatively constant through the year. This represents an excellent resource for solar photovoltaic. However, such resource remains untapped as the PV installed capacity until 2019 was only 2.4 GW. This is still a shallow fraction of what could be achieved (The World Bank Group, 2021).

The purpose of this study is to propose a suitable site that allows cost-effective installation of large-scale FPV installation on Lake Nasser, while simultaneously reducing evaporation losses. It analyses state-of-the-art FPV technologies while considering and comparing their specific features in order to predict the potential power

production and respective water evaporation savings from a practical perspective.

2. Floating photovoltaic systems: Technology overview

Floating solar, or FPV is an emerging fast-growing technology that makes use water bodies to produce renewable energy. Projections show that the number of projects will increase at an average rate of 20% until 2025 (Haugwitz, 2020). Although most of the FPV projects are relatively small in size with a mode of 1.7 MW, FPV plants of up to 150 MW are already operating.



Fig. 1: Floating PV Structures - (a) Pure floats, (b) Modular rafts, (c) Membrane float (Source: DNVGL)

Among the many advantages of FPV systems are the opportunity to scale-up solar energy generation without competing for available land -a special asset for countries with high population density-, improvements of water quality owed to decreased algae growth, and of particular interest to this study, the reduction of water losses due to evaporation, and improved electricity generation of the PV modules as a result of lower operating module temperatures. The following sections cover the latter two more in detail. In addition to these, FPV systems can be strategically combined with hydropower plants to operate in synergy, where the solar array can take advantage of the already existing grid infrastructure, and together provide a more stable and flexible power generation.

FPV systems have a similar layout to the land-based ones, with the distinction that the modules and often the inverters are mounted on floating platforms. These floating structures are fixed with moorings either to nearby solid points on land or anchoring system on the water body's ground. Floating structures are typically divided into three main categories: pure floats, modular rafts, and membrane floats (see Fig. 1). Following are their main characteristics:

- Pure floats: These floating structures are characterized by the direct mounting of the PV modules onto solid floats that are typically made of High-Density Polyethylene (HDPE), making them robust to harsh conditions and strong wind speeds. They are designed to have a single, specific inclination angle, which depends on the float itself and the selected manufacturer. Typical values are between 5° and 22° (see Tab. 2).
- Modular rafts: These systems are distinguished by having a structural framework made of galvanized aluminum or stainless steel that is supported by floats. In this case, there is more flexibility regarding the tilt angle. Because the floaters do not fully cover the water surface where the system is placed, good ventilation under the modules allow for a cooling effect to be generated.
- Membrane floats: A relatively new technology where PV modules are attached to a reinforced membrane that is supported by a HDPE tubular ring. The whole structure formed by this ring and the membrane is providing buoyancy. Modules are placed plane on the membrane surface (tilt angle = 0°). The flat design is making this system more resilient to strong winds and waves.

The floating platform is an essential component of the PV installation, and the selected type will play a preponderant role in the project's priority: water evaporation reduction or energy generation.

3. Data and methods

3.1 Suitable site for large scale FPV on Lake Nasser

Selecting an adequate location for the FPV plant is key for a successful project. The selection criteria for the FPV system to be deployed on Lake Nasser is to find an area suitable for installing min. 4 GW_p , a location where investments costs are low, operation is safe, and preferably considering a region of Lake Nasser, which shows relatively high evaporation rates, so that potential water savings are maximized. According to (El-Shazli et al., 2018) which analyzes 3 evaporation measurement stations on Lake Nasser, highest evaporation of

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2,884 mm is observed at the Raft station near the Aswan dam in the North. Reasons may be the slightly higher water temperatures in the North, but mainly the drying effect of the predominant NW to NE winds. Due to its quite large open water fetches in many parts of Lake Nasser significant wave height can build up, which would require installing substantially more expensive FPV or wave braking structures, which can withstand or destroy the waves. From planning other FPV projects we are aware of the high costs of mooring systems in deeper waters. Thus, although bathymetry was considered for site selection. Further, a nearby high voltage power line would be an advantage for lowering costs.

Considering all mentioned site selection criteria, a shallow, well protected part in the NW of the Lake is selected (see Fig. 2). Based on satellite-derived mapping of evaporation (Hassan, 2013; El-Shazli et al., 2018, p.) this part of the lake shows higher evaporation rates than the main lake - presumably due to higher water temperatures in this shallower part of the Lake Nasser. Hassan (2013) for this part indicates average annual evaporation of 2440 mm, while for the area of the Raft station only 2400 mm is given. For the Raft station this is substantially lower than the measurement derived. However, it must be noted that the evaporation rate at the selected site -and the one used on the present study- varies with respect to this figure. This is because the climatic conditions at the site under study are different, specifically temperature, relative humidity, wind speed and elevation. Further discussion is found in the following sections.



Fig. 2: Lake Nasser - Overview of selected site

The chosen remote part of the lake is well protected from larger waves building up occasionally in the main part of Lake Nasser. Distance from the 380 kV power line is only 10 km. Total area of this section of the lake is close to 90 km². Of this large site, several larger sub-areas have been identified which are in total providing suitable areas for FPV with a total of up to 56 km². The aim of this is to follow the Solar Energy Research Institute of Singapore (SERIS) recommendation of covering a maximum of 60% of a surface to prevent concerns about oxygen levels and amount of sunlight reaching the water.

3.2 Climatology of the site

The selected site was analyzed with regard to its solar resource potential using multiple data sources. An estimation of the expected long-term average Global Horizontal Irradiance (GHI) – called "best estimate" or P50 value – was performed, which is closely related to the potential photovoltaic power yields. Tab. 1 shows the main results. The inter-annual variability at this site is calculated using the long-term time series of PVGIS-SARAH and amount to 0.6 %, which is considered very low. Fig. 3 illustrated the annual cycle along with the average, maximum and minimum daily Global Horizontal Irradiation (GHI) and temperature to be expected.

Parameter	Value
Average air temperature	25°C
Maximum	35°C
Minimum	15°C
Max. relative humidity	55.4%
Min. humidity	4.6%
Max. wind speed	5.6 m/s
Min. wind speed	3.5 m/s
Direct Normal Irradiance	2759 kW/(m ² a)
	$= 315 \text{ W/m}^2$
Average of Global	2305 kW/(m^2 a)
Horizontal Irradiance	$= 263 \text{ W/m}^2$



Fig. 3: Global Horizontal Irradiance (left) and Air Temperature (right) of the selected site. Lighter colours show maximum and minimum values of daily-averaged values during each month.

3.3 Engineering design

Conventional PV plant designs involve the utilization of the ideal inclination angle for the module, where the tilt angle is optimized taking into account the site's latitude in order to harvest the most irradiance that can hit the plane. However, for FPV plants this is a restricted parameter, as the tilt angle is limited by the design of the float. Other important parameters, such as the distance between rows and the necessary area for the platform are conditioned by the architecture of the floating system, and hence, by the manufacturer. For this reason, the potential of FPV in the selected site analyses the three currently available floating structures. Given that in the current market there are different manufacturers for each type of structure, nine designs from four different suppliers were studied. A summary of the designs and specifications considered on this study can be found on Tab. 2.

Supplier	Floating structure	Tilt angle and orientation	Pitch distance		
А	Pure float	5°, south oriented	1.97 m		
А	Pure float	12°, south oriented	1.97 m		
А	Pure float	15°, south oriented	1.97 m		
А	Pure float	22°, south oriented	1.97 m		
В	Pure float	5°, south oriented	1.13 m		
С	Modular raft	5° east-west oriented ¹	4.55 m		
С	Modular raft	10° east-west oriented	4.55 m		
С	Modular raft	15° east-west oriented	4.55 m		
D	Membrane	0°	1.23 m		

Tab. 2: FPV studied systems and their main respective design considerations

FPV plants are built in terms of blocks or islands, where their size will depend on the conditions of the site and characteristics of the project. A typical block size is 10 MWp. Hence, the present study has taken this value as the first premise for the design. A targeted DC/AC ratio of 1.2 has been established, and tier-1 modules and inverters have been considered.

There is no strict recommendation regarding the type of PV module for solar floating plants; however, dualglass modules have shown more resilience against highly moisturized environments and together with their butyl sealant for the edges, electrical components can be hermetically protected (Kempe et al., 2017). Therefore, a bifacial 545 W_p module has been selected for the simulations. As for the inverters, the industry has not shown a clear preference regarding CAPEX, OPEX and yield for central and string inverters. Nevertheless, the general recommendation that for big plants, central inverters avoid the complex cabling and ohmic losses that string inverters would imply. Therefore, a central inverter has been used for the simulations.

3.4 Power generation: simulation parameters

The amount of electricity that a PV system can generate is site-dependent, being the quality of the solar

 $^{^{1}}$ East-west oriented systems are arranged in a way that half of the modules have an azimuth angle of -90° and the other half +90°

resource the main driver. Various factors play a role on the final energy outcome, and although the efficiency is related to the design and selected components, environmental factors need to be considered. The overall methodology to estimate the energy production for a FPV plant is similar as to a ground-mounted system. However, as the system lays above water, certain parameters will behave differently, namely the thermal parameters, soling, and mismatch. The following sub-sections discuss this further.

3.4.1 Thermal losses and cooling effect

One of the major advantages that is attributed to FPV systems is the so-called cooling effect, which enhances energy production compared to land-based systems. The temperature at which a solar cell operates is of significant importance, as it determines the performance of the module. It is a result of the incident solar radiation, ambient temperature, wind speed and wind direction (Dörenkämper et al., 2020). This is represented by the thermal loss factor, or U-value. The general rule is that lower ambient temperatures lead to lower operating cell temperatures, and hence to a better performance. The U-value is described by eq. (1):

$$U = U_0 + U_v \cdot w \qquad \text{eq. (1)}$$

Where U_0 is a constant component and the second term is a factor proportional to the wind speed, *w*. This equation represents the standard approach utilized on ground-mounted systems, where a value of 29 W/m²K is utilized. However and as stated by (Lindholm et al., 2021), FPV systems have a different interaction with the environment, and its modelling will depend on the type of floating structure. The U-value should account for the heat loss on both surfaces of the module. Thus, eq.(1) can be rewritten as follows:

$$U_{total} = U_{front} + U_{back} \qquad \text{eq. (2)}$$

The reason behind it is that the heat transfer coefficient, which accounts for convection and thermal radiation that are necessary to calculate the temperature of the cell, is different when modules are cooled by air on both sides -as in the case of modular rafts and pure floats-, or when they are in thermal contact with water, and hence cooled by air on one side and water on the other. Lindholm et al., 2021 determine that floaters with direct thermal contact with water benefit the most and have U-values in the range of $78.7 - 94.2 \text{ W/m}^2\text{K}$, whereas floating systems that prevent the modules to have direct thermal contact with water have a similar behavior to land-based systems. On the other hand, structures that allow for ventilation are found to have a median U-value of $47 \text{ W/m}^2\text{K}$.

Even though high U-values have an influence on the energy yield, the relation between these two is not necessarily linear. Far after solar radiation, the temperature of the PV module has the greatest influence on the power output, but still, the extent to which such temperature is lowered depends enormously on the region. This was demonstrated by Dörenkämper et al. (2020), where two climatic zones were compared -a tropical and a temperate maritime climate- and results showed that although having relatively high U-values, the increase in yield compared to a reference land-based system was only of 3% and 6% respectively.

3.4.2 Adaption of meteorological data

Specific characteristics of a site of interest, such as relative humidity, pressure, wind speed and dry bulb temperature are collected on a Typical Meteorological Year (TMY) file, which is later used as input for the energy simulations. However, values do not always account for the conditions of FPV systems, especially wind speed (v_w) and ambient air temperature (T_a) . For this reason, an adaption of these two elements has been done on the TMY file. Following (*Hsu*, 1986) approach, wind speed was corrected according to the following equation:

$$v_w = 1.17 v_{land} + 1.62 \frac{m}{s}$$
 eq. (3)

Where (v_{land}) refers to the wind speed above land. This approach has been taken for FPV stand-alone designs, such as the one done by (Umoette, 2016). Similarly, ambient air temperature, T_{air} , above water is lower than on land. In order to account for it, the following correction has been done:

$$T_a = 0.9282T_{air} + 0.0246T_w$$
 eq. (4)

Where T_w is the temperature underlying the water body. Eq. (4) is based on the model and findings from Charles Lawrence Kamuyu et al., 2018.

3.4.2 Soiling losses

Given that solar arrays operate under open sky, they are subject to the cumulation of dust, bird droppings, and depositions of microparticles that affect the system's performance. Such are known as soiling losses. Factors as dust mass concentration, wind speed, wind direction and relative humidity are major contributors (Javed, Guo and Figgis, 2017). Because representing the dynamic behavior that these variables have among each other is a very complex task, it is common to find simulations that utilize values in the range of 1-3% (World Bank Group, Solar Energy Research Institute of Singapore and Energy Sector Management Assistance Program, 2019). Such assumption is valid for ground-mounted systems, where typically the tilt angle is high enough to allow for self-cleaning, particularly during rainy seasons. However, such approach can underestimate the real effect of soiling on FPV systems as tilt angles are typically low.

Following the findings of (Kimber et al., 2006; Tamizhmani, Macia and Cano, 2014), soiling can be modeled as a linear degradation. Based on the results from Tamizhmani, Macia and Cano, 2014, an equation that describes the soiling loses as a function of the tilt angle has been determined:

 $y = -0.0002\beta^3 + 0.0112\beta^2 - 0.1732\beta + 2.0036 \qquad (eq. 5)$

Where y is the percentage of soiling losses and β represents the module's tilt angle.

3.4.3 Mismatch losses

When the amount of irradiance that hit a string of modules is different, the so-called mismatch losses occur. In this case, the current of the panel with the lowest irradiance will drop, limiting the performance of the entire string. Ground-mounted systems usually adopt values of 1%. However, the constant motion of water together with waves, currents and wind make FPV systems subject of a constant movement, thus adding for this kind of losses. According to studies ran by (Dörenkämper et al., 2021) on sites with different wave categories and wave heights, the minimum value found for mismatch losses was 3%. On the same report, it was noted that flexible systems based on HDPE floaters were especially vulnerable to this effect. Hence, it can be assumed that the potential losses for pure-float systems is higher than 3%.

3.5 Evaporation reduction

Estimations for evaporation rates at Laker Nasser have been previously done by different authors. *El-Shazli* et al., 2018 elaborated a study comparing three different locations along the lake and used several methods to calculate daily evaporation values. However, this values cannot be directly assumed for the site under study of the present analysis, as evaporation strongly depends on the site's meteorological characteristics, and as it has been proven, small differences on air temperature, wind speed or relative humidity can lead to diverging results ELMekkawy, Salah and Abdel Wahab, 2018. For the present study, solar resource assessment was carried out which also provided the necessary input data to apply evaporation calculation using the Penman-Monteith Evaporation Model.

3.5.1 Penman-Monteith model

A number of empirical methos have been developed to estimate evaporation based on climatic parameters. The Penman-Monteith equation combines energy balance with mass transfer to estimate evaporation on open water bodies. This model is well known in the literature for its accuracy (*Van Zyl and De Jager, 1987*), and therefore has been selected as the model for current evaporation estimation on the selected site. It is represented by eq.(6):

$$E = \frac{0.404\Delta(Q^*-N) + \gamma \frac{900u_2(e_S-e_a)}{T+273}}{\Delta + \gamma(1+0.34u_2)}$$
(eq. 6)

Where E is the evaporation rate, Δ the slope of saturation vapor pressure curve, Q* the net radiation in MJ/m²d, N the soil heat flux density in MJ/m²d, γ the psychometric constant, u₂ the velocity of the average wind at 2 m height, e_s the saturation vapor pressure in kPa and e_a the mean actual vapor pressure, also in kPa.

3.5.2 Water coverage ratio

A relevant factor influencing water evaporation is the amount of solar radiation that hits a surface. FPV reduces evaporation because it acts a barrier between such radiation and the water. This is known as direct evaporation. However, an indirect effect also occurs as a result of the cooled water in the surroundings of the FPV system, which indirectly prevents evaporation to occur. This study focuses solely on the direct evaporation.

Water Coverage Ratio (WCR) is defined as the percentage of the water surface that is in direct contact with a floater, and it will differ from floater type and supplier.

4. Results

4.1 Energy production

PVsyst software version 7.2.6 is applied for analyzing the performance for each floater manufacturer and for different configuration. A representative shading scene is built to assess the respective shading losses. All simulations are based on a site-specific typical meteorological year (TMY) with hourly time resolution as explained in section 3.2. Additionally, relevant loss factors resulting from the plant's location, components and configuration were assessed and considered for the simulation.

The simulations are based on blocks of 10 MW_p FPV. Fig. 4 shows the energy performance results of each floater type and for different configurations. The difference in the thermal parameters and the cooling effect, mismatch, panel orientation (landscape and portrait) and the number of modules that can be installed within the same area, plays a major role for the performance of each floater type.



Energy injected to the grid (MWh) • Performance Ratio (%)

Fig. 4: Energy production and performance ratio for the analysed FPV designs

As it can be observed, all of the systems behave similar, where the difference between the highest and lowest generated energy is equivalent to 2,784 MWh. Taking a closer look to systems A and B, which belong to the same category -modular rafts- it is also observed that system A behaves better. This is the effect of lower distance between rows (pitch). System B, whose pitch distance is equal to 1.13 m, is being subject to higher shading losses, and hence, energy production is reduced.

Considering the effect of the tilt angle, the general trend is that the higher the tilt, the higher the energy production as systems can harvest most of the solar radiation hitting the module. However, this trend appears to be contradicted by systems A and C, particularly for those with angles of 10° , 12° , 15° and 22° . In the case of system C, such behavior results from the East-West orientation of the modules, which with an increasing angle, shading becomes more pronounced leading to less energy.

As it was previously discussed, the architecture and dimensions of the floating structure is not the same for every system; it varies from one manufacturer to the other. Hence, the required area for a10MWp block will differ among them, and as a result, the number of blocks that can be deployed on a restricted surface will be different. Taking this into consideration, an estimation of the number of blocks that fit the 56 km² of the selected site has been calculated. When a FPV system is deployed, blocks are not placed directly next to each

other as the water motion could cause them to hit against one another. For this reason, a distance of 15 m between blocks was included in the calculation. Based on this numbers, it is possible to scale up the energy potential for each system. Results are displayed on Tab. 3.

Tab. 3: Potential energy production per manufacturer based on their respective number of blocks					
Manufacturer	Area _{10MW Block}	Nb. of blocks to fit the total are of	Electricity generation potential (TWh)		
	(KIII)	the site	Min.	Max.	
А	0.107	478	9.61	9.94	
В	0.056	886	17	.24	
С	0.048	1020	21.019	21.59	
D	0.094	595	12	.43	

4.2 Water savings from evaporation reduction

Water savings were calculated based on the evaporation rate obtained from the Penman-Monteith model, which resulted on an average of 9.23 mm/day. This value lays in the range of previous elaborated studies in the proximity of the region (El-Shazli *et al.*, 2018).

From Fig. 5 it can be observed that water savings differ significantly from one system to the other, reaching values of up to 177 Mio m³ per annum. As discussed in section 3.5.2, this assessment is focused on direct evaporation, which is related to the WCR. Based on online available data and direct conversations with manufacturers, the WCR of each system has been estimated. Results of this, together with a summary of the area that each floating system would require to cover 10%, 50% and 100% of the site, as well as the installed capacity, energy production and water savings can be



Fig. 5: Water savings as a function of the covered FPV area

found in Tab. 4¹. It is clear that the manufacturer whose floater covers entirely the surface where it is deployed is the one with the highest water savings. However, the highest energy production potential belongs to manufacturer C, which happens to have the lowest WCR. This is because as depicted in Tab. 3 the architecture of such system allows a larger number of blocks to be installed.

Manufac	WCR	C	Covering 10%	% of the sel	ected site		Covering 50	% of the sele	ected site	Co	vering 100	% ² of the	selected site
turer	(%)	A _{Block} (km ²)	IC (MW _p)	EP (TWh)	Water Savings (Mio. m3/annum)	A _{Block} (km ²)	IC (MW _p)	EP (TWh)	Water Savings (Mio m3/annum)	A _{Block} (km ²)	IC (MW)	EP (TWh)	Water Savings (Mio m3/annum)
А	48%	5.10	478	0.95	8.3	25.48	2,392	4.75	41.3	50.95	4784	9.59	82.6
В	85%	4.95	886	1.70	14.2	24.77	4431	8.54	70.9	49.51	8,863	17.07	141.8
С	10%	4.93	1,028	2.15	1.7	24.66	5,142	10.73	8.3	49.32	10,283	21.46	16.6
D	100%	5.26	596	1.20	17.7	26.31	2978	6.04	88.7	52,67	5,956	12.08	177.3

Tab. 4: Area, installed capacity, energy production and water savings for each system considering different fractions of coverage area.

WCR: Water Coverage Ratio

 $A_{\rm Block}$: Area that the floating structure would occupy to cover the surface of the site's surface IC: Installed capacity

¹ To illustrate conservative results, Energy potential (EP) is based on the lowest values of generated energy from each manufacturer

² 100% covered area = 56 km²

EP: Energy production

5. Influence on hydropower electricity generation

An additional advantage of FPV systems is the possibility of deploying them on hydropower dams. Both systems have the potential of work in symbiosis, where the solar plant could operate during dry periods, and at the same time, hydropower could compensate for PV's intermittent power generation. However, even when both systems do not work in synergy, water saved from evaporation would mean additional water volume is available for electricity production. Following Gonzalez Sanchez *et al* 2021 rationale, the nominal power capacity of a hydropower station is described by eq. (7):

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot h \qquad \text{eq. (7)}$$

Where η is the system's efficiency, ρ is the water density, g is acceleration of gravity, Q is the nominal water discharge of the turbines in m³/s, and h is the hydraulic head in m. Given the volume of the water savings, V (m³), according to Gonzalez Sanchez *et al.*, 2021 a hydropower station could operate at full power for an additional number of hours, T, where

$$T = \frac{Q}{V} \qquad \text{eq. (8)}$$

Finally, the additional electricity is calculated by the product of $P \cdot T$.

According to the study realized by the Egyptian Electricity Holding Company and Hydro Plants Generation Company, 2016, the Aswan High Dam has a nominal capacity of 2,100 MW at a nominal water discharge Q of 11,043 m³/s. In addition, the Aswan Low Dam with a nominal capacity of 592 MW also profits from the increased amount of water volume. Assuming FPV case D with the highest water savings of 177 km³/annum, an additional 4.6 full load operation hours is given. This leads to an additional combined hydropower electricity production of 12 GWh per year. Compared to the very high additional electricity amount generated by this FPV layout this would be only 0.1% of this production. But compared to the current average hydro power generation of the Aswan High and Low Dam the reduction of evaporation on the upper reservoir provides a small but significant increase.

An additional advantage is the fact that FPV power production is highest during summer, when solar radiation is strongest and water levels of Lake Nasser decrease due to enhance evaporation. This is the time, when hydropower production is lowest in the annual cycle, but with more and more air conditioning installed power demand is strongly increasing.

The greatest advantage of connecting control of such huge FPV system with the Aswan High Dam hydropower system is, that the combination of the Aswan High and the Aswan Low Dam can be utilized as a huge battery system. Due to the direct connection between both large reservoirs continued water release from the lower dam can guarantee required minimum flow rates in the river downstream, while the turbines of the upper dam can be completely shut when FPV production is high. As the installed PV peak power of the proposed FPV cases utilizing the full 56 km² available depending on selected FPV technology is 4 to 10 times higher and solar irradiation at this site is very high at most days, there will be plenty of days where for around 10 h the water flow from the upper reservoir could be completely stopped. In addition, the saved water during the day leaves the opportunity to release more during evening and nighttime, when power consumption in Egypt also is raising. This excellent power storage utilization could be further improved when the turbines would be extended by pump functionality. For quantifying the full potential of such combination, it is recommended to analyze this in combined simulations.

6. Conclusions

Lake Nasser, Egypt's primary source of water and a major provider of hydroelectricity has the potential to deploy large-scale floating PV systems to produce electricity while simultaneously save water by reducing evaporation. The present study focused on a site located at the north-west of the lake, whose total surface area is equivalent to 90 km². However, to avoid environmental concerns related to water oxygenation and sunlight reaching the surface, a restricted area of 56 km² was selected to potentially deploy FPV systems.

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After elaborating a solar resource assessment, findings showed that the solar characteristics at the site are excellent, with an average global horizontal irradiance equivalent to 263.1 W/m^2 or $2305 \text{ kW/(m}^2 \text{ a})$. Four different types of floating structures belonging to state-of-the-art manufacturers are analyzed, while taking into consideration their design characteristics, such as allowed tilt angle and pitch. Additionally, the electrical behavior derived from environmental conditions of FPV systems were included, namely heat loss coefficient, soiling and mismatch losses. A modification of the Typical Meteorological Year (TMY) file -used to run simulations on the PVSyst software- was done in order to account for the environmental conditions that solar systems placed above water are subject of.

A 10MWp block design was used as a basis of the simulations. At the same time, it has been discussed that evaporation savings are a function of the area covered by the FPV system -the Water Coverage Ratio, which varies from manufacturer to manufacturer. Under these considerations, results showed that in spite of its differences, the four systems behave similarly producing values in the range of 19,265 MWh to 22,238 MWh. However, their dimensions play an important role in the total site's potential, as the required area to deploy a 10 MWp block varies significantly, allowing some systems to be deployed in greater number than others.

From a covered-area perspective, results showed that covering the total 56 km² with a modular raft floating system -the floater with the lowest WCR- there is a potential of generating 21.46 TWh. This results from the system's dimensions, which gives it the capacity of being deployed the most compared to the other three. On the other hand, water evaporation reduction reaches its peak levels with the membrane floating system is capable of saving up to 0.177 km³ per year. This is due to its large WCR.

It must be noted that the evaporation figures presented on this report are the minimum amounts of water that could be saved, as the focus was on direct evaporation. If diffuse evaporation would be included, figures depicting water savings would be higher.

When placed on a hydropower plant, FPV systems offer the additional advantage of (1) working in synergy, strengthening the system's resilience against volatile climatic conditions, and (2) utilizing the saved water for extra electricity generation. In the case of Lake Nasser, an additional annual hydro power generation of 12 GWh could be expected for the case where around 1% of the Lake's surface are covered by the FPV technology, which is providing the highest water saving effect.

FPV is still an emerging technology, and the advantages that could be reached with this kind of systems is still to be untapped. Lake Nasser possesses many characteristics that make it ideal for the deployment of FPV, and many potential opportunities for the Egyptian country in terms of battling water scarcity and satisfying the electricity demand of its increasing population lay on the lake's water surface.

7. Acknowledgments

This work was supported by Suntrace GmbH. We would like to thank Simon Weber and Prof. Dr. Hans Schäfers for their contributions and support.

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D-03. Building-Integrated Photovoltaics

Building Integrated Solar Technology – Evaluating 20 Years of Experience with Solar Buildings from an International Competition

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Abstract

The "Architectural Award Building Integrated Solar Technology" was established in 2000. The aim of this prize is to make exemplary solutions at the interface between architecture and solar energy accessible to a broad public. Since then, eight competitions have been held, with around 40 prize winners and almost 600 projects submitted from all over the world. The competition entries show the great potential of coherently integrated solar technology as part of ambitious architectural and energy building concepts. In the article, examples from the competitions are used to illustrate continuous further developments and, above all, design innovations in the field of building-integrated solar technology (with a focus on photovoltaics).

Keywords: Building Integrated Photovoltaics (BIPV), Solar Façade, Solar Buildings, Solar Architecture

1. Preliminary remarks on the context

The use of solar energy in and on buildings is a central aspect of energy-efficient construction – for homes, industrial and administrative buildings as well as residential complexes. The Solarenergieförderverein Bayern (SeV) [https://www.sev-bayern.de <12.10.2021>] has held eight competitions on the topic of "Building Integrated Solar Technology" with around 40 prize winners since 2000. The thematic focus and geographical orientation changed over the years. Initially, the competition only targeted PV façades in Bavaria and Germany. Then there was an opening up from photovoltaics to solar technology (including solar thermal collectors) and building envelopes. As of 2011, there are no longer any national restrictions.

The aim of the competitions is to make exemplary solutions in qualitatively demanding architecture accessible to a broad public. In the years between 2000 and 2005, only a little more than a dozen entries from Bavaria and Germany were represented at any one time. After the opening for European and worldwide submissions, a continuous increase in the number of participants can be observed. The 2020 competition attracted 159 entries, of which 146 were ultimately in the "Architectural Award" competition. In total, the eight competitions now comprise almost 600 submitted projects from 43 countries. (Fig. 1)





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Fig. 3/4: Nikolaus-Fiebiger-Zentrum, Erlangen (2000), Universitätsbauamt (left) and Holz-Berufsgenossenschaft, München (1999), pmp Architekten (right)

The example of the competition activities of the SeV, founded in 1997, can be used to show the increasing broad impact and establishment of the topic in the following decades. What are the continuities in the field of building-integrated solar technology and how have construction and especially design strategies changed in the last 20 years? Solar systems with a focus on photovoltaics will be examined, but in addition to roof solutions, the focus will be on PV façades, as some particularly striking developments can be identified here.

2. About the competitions

A cursory look at the first phase at the end of the 1990s – in which one can speak of "building-integrated solar technology" in a certain broader sense, beyond a few pilot projects – shows that a wide range of possible applications of solar technology has already been successfully tested in architectural practice, even if some of these projects are only known to experts.

2.1. Solar power systems and PV façades in Bavaria and Germany (2000 - 2005)

The example of the competition winners in particular can be used to illustrate very clearly strategies in the use of photovoltaics in architectural concepts. (Krippner, 2017, pp. 8-19) Due to the tender conditions, three façade solutions that are still current today were initially awarded. (SeV-Bayern, 2002 and SeV-Bayern, 25.07.2005).

In 2000, the competition is held for the first time under the title "Innovative building-integrated solar power systems in Bavaria". Among the 16 projects submitted, the Nikolaus Fiebiger Centre of the Friedrich Alexander University in Erlangen (2000; Erlangen University Construction Office, Christof Präg) demonstrates the potential of integrating PV modules. A slightly curved "solar awning" is arranged on the top floor of the south façade, while the façade of the lower structure is extensively equipped with horizontal, single-axis tracking PV glass louvres. The photovoltaics blend in perfectly with the technical aesthetics of the research building (Fig. 3).

2001, the subsequent competition "Solar Power from Façades" was announced, to which projects from all over Germany were admitted. Out of ten buildings submitted, the headquarters of the Holz-Berufsgenossenschaft (1999) in Munich by PMP Architekten was awarded 1st prize. In the almost 50 m high building, polycrystalline PV modules are arranged both in a cold façade in a narrow vertical strip and as solar protection in a partial area of the warm façade. A wider and a narrower strip extend from the third to the eleventh floor, each emphasising the vertical in the distant view, but horizontally divided by the cover strips in the near view (Fig. 4).

In 2005, the third competition was held under the title "Architecture and Solar Power - Building-Integrated Photovoltaic Systems". The competition shows a clearly higher design quality. First prize was awarded to the architects Rolf + Hotz for the renovation of two nine-storey apartment buildings (2001) in Freiburg from the second half of the 1960s. The closed south façade is characterised by a building-high, interconnected PV system. The glass-glass modules, arranged in landscape format, are attached to the aluminium substructure on the long side with visible black clamping profiles. The project shows how PV façades can be implemented in an exemplary manner, both technically and in terms of design, even in renovations (Fig. 5). (Krippner, 2015)

2.2. European and Architectural Award for Building-Integrated Solar Technology (2008 - 2020)

Since 2008, the SeV has held the competition every three years, expanding it to include solar thermal and roof systems and opening it up internationally – initially as a "European Prize".



Fig. 5/6: Punkthäuser Wilmersdorfer Straße, Freiburg (2001), Rolf + Hotz Architekten (left) and Marché International, Kemptthal (2007) Kämpfen für Architektur (right)

In the 2008 competition, the jury reviewed 38 projects from eight countries. (Becker and Krippner, 2009) The European Prize for Building-Integrated Solar Technology was awarded to a new office building for Marché International in Kempthal (2007). This is considered to be the "first office building in Switzerland with a real zero-energy balance". In combination with a clear architectural concept and a compact structure, Beat Kämpfen succeeded in creating an exemplary solution for administrative buildings that generate the energy required for operation themselves. The monopitch roof is designed as a full-surface electricity generator and supplies 100 % of the required electrical energy. The architects succeeded in unobtrusively but extremely carefully and elegantly detailing the roof and its edges (Fig. 6).

For the first time, projects from all over the world are eligible for the 2011 Architectural Award. Even though most of the 84 entries came from German-speaking countries, the response from a total of 13 countries confirms the openness of the process. (Becker et al., 2012) With the new construction of a carpenter's workshop (2010) near Freising, this time the architecture prize is awarded to a type of building where design demands are otherwise often rare. Deppisch Architekten designed a formally reduced, elegant structure in which not only the south-facing surface (20 degrees) is fully covered with photovoltaics, but also the more gently sloping north-facing surface (10 degrees). The PV system is flush with the roof edges, resulting in a two-dimensional appearance. With a plausible overall concept, the PlusEnergy standard is achieved (Fig. 7).

In 2014, the competition underlines the topicality of the subject, both quantitatively and qualitatively, which in the meantime threatened to be somewhat lost from the field of vision of architects and building owners due to the economic problems of the solar industry. 137 projects submitted from 20 countries represent an increase of over 60 percent compared to 2011. (Krippner et al., 2015) The architecture prize was awarded to René Schmid Architekten with the UmweltArena in Spreitenbach (2012). The new building is dominated by a prismatically folded roof with 33 differently inclined and exposed sections. The long sides are oriented to the southwest and northeast, but the north-facing roof surfaces are also solar-activated with monocrystalline, frameless glass/glass modules. The solar yield exceeds the arena's own energy requirements by a factor of two (Fig. 8).



Fig. 7/8: Hall design.s, Pulling (2010), Deppisch Architekten (left) and Umweltarena, Spreitenbach (2012), René Schmid Architekten (right)



Fig. 9/10: Hof 8, Schäftersheim (2014), Architekturbüro Klärle (left) and Lycée technique pour Professions de Santé, Ettelbrück (2019), Fabeck Architectes (right)

In the 2017 competition with 119 evaluated projects, it can be seen that only a good third (\approx 34 percent) still come from Germany. Due to the strong share of submissions from Switzerland and Austria, the German-speaking region is around 77 percent. The growing number of participants from non-German-speaking countries, especially from Scandinavia and the Benelux countries, is encouraging and shows that the competition continues to gain considerable international recognition. (Krippner et al., 2018)

The prize winner, the PlusEnergy building complex "Hof 8" in Schäftersheim, makes a contribution to a topic determined by numerous challenges in a holistically designed concept: building in rural areas. In addition to a coherent mix of uses, the use of regional products and the reuse of materials in order to minimise the proportion of grey energy in construction, photovoltaics are fully integrated into the roof surfaces of the farm ensemble. In terms of construction, a rather conventional rooftop installation is chosen, which, however, captivates through the carefully detailed treatment of the roof edges. The combination with existing quarry stone masonry and new timber façades also illustrates the design potential of commercially available solar technology (Fig. 9).

In October 2020, with 159 projects, the field of participants has almost doubled compared to 2011, and even compared to the previous competition in 2017, there has been an increase of 20 percent. The country-specific distribution also shows an increase with 26 countries, although submissions from Germany and Switzerland clearly continue to dominate, each accounting for more than a third. (Krippner et al., 2021)

This time, the "Architecture Prize" is awarded to a school building in Ettelbruck. The four-storey building is divided by a projecting and a receding structure. The primary construction is made of wood, except for the escape staircases. Asymmetrical gable roofs vary in pitch and are fully covered with PV modules. The PV generator on the roof surfaces is carefully implemented on a wooden substructure with painted connection plates and continues familiar approaches of structural engineering practice. In the southwest and west façades, solar thermal collectors based on a post-and-beam construction are flush-mounted at the height of the opening edges. The chosen dimensions and proportions of the solar components complement the façade appearance with the vertically arranged narrow wooden strips in an excellent way (Fig. 10).



Fig. 11/12/13: Single family home, Hegenlohe (2005), Tina Volz and Michael Resch (left), opus House, Darmstadt (2007), opus Architekten (middle) and Weyerguet, Wabern (2019), Halle 58 (right)

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Fig. 14/15: Bus station, Bad Wörishofen (1995), GS Schneider Architekten (left) and Carport Waste Management Corporation, München (2011), Ackermann Architekten (right)

2.3. Continuities and changes - assessments based on selected examples of projects

Using projects from all competitions, some aspects of PV roofs and façades will be discussed. In the case of roofs, over the past 20 years a broad standard of exemplary solutions can be found both in award-winning projects and in everyday architecture. (Krippner, 2019) In many cases, fully integrated systems are implemented in a technically and design-wise coherent manner in a variety of building types. But rooftop solutions, such as the one-family house in Hegenlohe by Tina Volz/Michael Resch (2005) with precisely detailed implementation, can also be convincing. An elevated PV system is located on the flat, southwest-facing gable roof. The rows of modules are slightly guided over the eaves and ridge, the punctual fastening can be read off (Fig. 11).

The issue of existing buildings still poses a challenge, especially when requirements for the protection of historical monuments have to be taken into account. (Krippner, 2017) If one disregards the first two competitions with their "special conditions", it becomes apparent that measures in existing buildings still play only a subordinate role within the "Architectural Award", at around 13 percent (Fig. 2). Over the years, numerous competition entries, including those that have won awards, have shown exemplary, almost self-evident implementations and demonstrate that solutions are available.

In Darmstadt, Opus Architekten realised a combined system with rather conventional solar thermal collectors and photovoltaic modules in a historical ensemble (Fig. 10). In contrast, Halle 58 architects is using red PV modules in the renovation of the historic Weyerguet farmhouse (2019) in Wabern (Fig. 11). Both projects are exemplary for energy roof solutions in which both the building concept as a whole and the detailing of the solar technology are convincing.

Large-scale roofing is also becoming important, especially in combination with electric mobility. An early example is the bus station (1995) in Bad Wörishofen. GS Schneider Architekten use semi-transparent PV modules on an elegant steel structure in the southern surfaces of the roof construction (Fig. 14). For the roofing of the carport of the waste management corporation (2011) in Munich, Ackermann Architekten choose an innovative approach with flexible modules and foil cushions as a multifunctional roof: weather protection, use of daylight and electricity generation (Fig. 15).



Fig. 16/17: Ökotec 3, Berlin (1993), SJ Planungsges. (left) and Paul-Horn-Arena, Tübingen (2004), Allman Sattler Wappner (right)



Fig. 18/19: Nursery +e, Marburg (2014), opus Architekten (left) and Grosspeter Tower, Basel (2017), Burckhardt+Partner (right)

While there has been continuous development of the PV roofs, there have been significant changes in the façades over the years. In addition to the solutions discussed in the area of cold façades, two projects are exemplary for early PV façades. In the Ökotec building (1993) in Berlin, natural stone cladding is combined with glass modules in the façade. Apart from the visible fastening, it is striking that the modules were designed with horizontal PV cell strips at the time (Fig. 16). The Paul Horn Arena in Tübingen (2004) shows an unusual implementation for the early 2000s in terms of surface size and detail. Allmann Sattler Wappner designed the entire south façade with vertical-format modules with green polycrystalline PV cells in four different sizes. A white edge, pronounced by the foil laminate on the back, structures each module and the overall appearance of the façade. Here, the visibly applied photovoltaics also perform an important role as a communicator for renewable energies (Fig. 17).

From 2010 onwards, a change begins. Architects are seeking to reduce the PV cell in the overall area of the module. An example is the nursery +e (2014) in Marburg by opus Architekten. The shed-like roof structure with PV strips sloping to the south continues its structure vertically in the south-west façade. Here, the monocrystalline cells recede in favour of a uniform surface effect; a perfectly detailed glass façade is revealed (Fig. 18). In the Grosspeter Tower (2017) in Basel by Burckhardt+Partner, the façade is characterised by a clear grid structure with openings that widen towards the top. The opaque façade surfaces consist of CIGS thin-film solar modules. Due to the different dimensions and architectural requirements, there are around 450 different types of façade elements, which are suspended in the substructure via support profiles on the back. The result is a homogeneous surface that is an elegant and efficient alternative to stone and metal façades (Fig. 19).

However, it is not only architects who are increasingly criticising these dark, anthracite-coloured PV modules. Colourfulness has been significant for building-integrated solar technology since the pioneering years; the widest possible range is often highlighted as a particular advantage of photovoltaics. In recent years, printed or coated modules, sometimes in combination with special glass, have also enabled solutions in other colours. For example, in the case of the apartment building (2018) in Zurich, Beat Kämpfen uses PV modules with multicoloured printing (50 percent of the surface), which gives the façade a reddish-brown appearance (Fig. 20).



Fig. 20/21: Multi-family home Höngg, Zürich (2018), Kämpfen Zinke + Partner (left) and Solaris, Zürich (2017), huggenbergerfries Architekten (right)



Fig. 22/23: Oskar von Miller Forum, München (2009), Herzog + Partner (left) and "Multi-family home with energy future", Zürich (2017), René Schmid Architekten (right)

In the Solaris residential building (2017), also in Zurich/CH, by huggenbergerfries Architekten, all opaque surfaces are covered with photovoltaics despite the complex geometry of the building. The architects' goal here was a "solar house that should not necessarily be recognisable as such". Monocrystalline modules are used with a prismatic front glass that is additionally colour-coated using a special printing technology. The vertical relief structure gives the glass surface a matt sheen and creates a variedly shaded, coloured play of light (Fig. 21).

In addition to colour, important issues in façade cladding are always fastenings and module dimensions or proportions. While non-visible fixings are now generally preferred, two projects show convincing solutions with visible hooks and profiles. Narrow PV louvres are arranged in front of the glazed access area at the Oskar von Miller Forum in Munich by Herzog + Partner (2009). The frameless glass-foil modules are each held in place by linear profiles on the long sides. Here, a few variations, both functional and constructive, in a clear overall structural concept result in an almost 'playful' solution (Fig. 22).

René Schmid Architekten chose a rather small-format module size for the multi-family house with energy future (2017) in Zurich. The façade planning is based on a clear modular grid, with over 1,000 monochrome glass panels of the same size, which brings cost advantages. In combination with the scaled arrangement on visible stainless steel hooks, an attractively structured division of the opaque surface is created (Fig. 23).

In a comparison of cold and warm façades, no such variance has yet been observed in the latter. The basic strategies of how crystalline cells can be used as parts of a mullion-transom construction are already shown by early examples from the SeV competitions. PV is almost naturally used in insulating glazing and often also serves as semi-transparent solar shading. Some projects also illustrate that the PV façade can also function as a status symbol, as in the SMA Solar Academy (2009) in Niestetal by HHS Planer + Architekten (Fig. 24).

In contrast, dye cells and organic photovoltaics open up different types of design. Richter Dahl Rocha & Associés used dye solar cells in this dimension for the first time worldwide at the SwissTech Convention Center (2012) in Lausanne. In the west façade, glass-glass modules with dye cells in different shades of yellow, green and red are arranged storey-high in front of the glass façade in narrow strips. These not only act as sun protection, but also create charming lighting moods in the foyer (Fig. 25).



Fig. 24/25: SMA Solar Academy, Niestetal (2009), HHS Planer + Architekten (left) and SwissTech Convention Center, Lausanne (2012), Richter Dahl Rocha & Associés architectes (right)



Fig. 26/27: Convention Center, León (2018), Dominique Perrault Architecte (left) and SIEEB, Beijing (2006), Mario Cucinella Architects (right)

3. (Interim) Conclusion – Building Culture: Architecture and Solar Technology

The Architectural Award of the Solarenergieförderverein Bayern e. V., with its focus on "Building Integrated Solar Technology", is now regarded as the leading event in its field in Europe, alongside the Swiss Solar Prize, which has been awarding prizes for buildings, best-integrated systems and architects since May 1990, and the German and European Solar Prizes, with which Eurosolar has also been honouring architects annually since 1994. Not only the award-winning examples show that in the meantime, in addition to solar thermal collectors, photovoltaics in particular have become a natural part of the building envelope of energy-efficient buildings in ambitious overall architectural concepts (Fig. 32/33/34). (Herzog et al., 2021 and Krippner, 2021)

When analysing pitched roofs, it can be seen that standard modules for on-roof or roof-integrated systems are usually chosen; only in the case of detached and semi-detached houses are special products such as solar tiles or specially shaped modules for roof integration sometimes used (Fig. 35). Very often, solar systems cover the entire roof surface, oriented towards the south, on a flat pitched roof facing south and north or as a prismatic structured building envelope.

In many buildings, the solar installation covers only partial areas of the roof. Very important for a coherent appearance is the design of the side surfaces with (colour-matching) flashings: Ridges, verges and eaves, as on the Convention Center (2018) in León. An almost 300 m long, flat-pitched roof on steel trusses spans the event and exhibition zones. The modules are mounted in single and double rows on six slightly unfolded fields of the roof surface, embedded in level maintenance corridors. Dominique Perrault Architecte from Paris thus succeeds in forming a multifaceted, large-scale energy roof of metal and glass in a historical setting. In addition, many projects now show unpretentious and carefully executed solutions that consistently follow familiar approaches from building practice (Fig. 26).

In contrast, some special features, but also problems regarding the form and character of the visual design of solar façades can be discussed. In terms of construction, applications in ventilated façades dominate - either in new buildings or in renovations. In the meantime, there are a number of projects in which PV systems are also installed in the balcony parapet area.

In terms of appearance, it can be seen over the years that crystalline PV modules with visible cells are now used rather rarely. Architects prefer modules with homogeneous surfaces, mostly in black – supplemented by anthracite-coloured thin-film modules. Modules with coloured imprints, coatings or special glasses are very common. An exception is the use of photovoltaics as (movable) sun protection, although there are instructive precursors. In the SIEEB (Sino-Italian Ecological and Energy Efficient Building) for Tsinghua University in Beijing by Mario Cucinella Architects (2006), for example, the PV lamella constructions cantilevered out floor by floor became an important element shaping the design. The institute building contains multiple overlaps of use and references to traditional Chinese symbolism. The different functional layers in the building envelope are brought to bear in terms of construction and design. In addition, there are projects with PV modules in non-ventilated façades, mostly post-and-beam constructions, in which – as a rule – the crystalline cells have a solar protection function (Fig. 27).



Fig. 28/29: Distribution of the solar technology used (left) and structural integration of solar installations (right)

Over a period of 20 years, it can be said that the quality of everyday architecture in the submissions has also increased significantly. The share of PV systems in the competition continues to grow, reaching more than 80 percent of the submitted projects in 2020. 14 percent of the buildings have combinations, the share with solar thermal collectors is only 5 percent. Despite the focus of the "Architectural Award" on "solar technology" since 2008, photovoltaics continue to dominate. In the past 12 years, pure solar thermal systems have hardly played a role; nevertheless, hybrid concepts in the roof and/or façade form a large project group with an average of about 21 percent. (Fig. 28)

Looking at the integration measures on the building, the development can be seen, especially since 2008, that pure roof systems (pitched and flat roof) comprise more than half of the projects on average. In view of the large number of façade systems (almost 20 percent) in the competition over the past 20 years, the state of the art and, at least in the case of the award-winning projects, design and construction ambition can be clearly demonstrated. (Fig. 29)

To participate in the competition, in addition to general author's declarations, information about the system components as well as detailed technical descriptions of the solar system, type of installation with technical details of the building integration, electrical or thermal output and annual yield up to the contribution of the solar systems to the energy supply of the building as well as the environmental effect are requested. In practice, only little such substantial information can be found in the documents.

Many award winners and projects from the "shortlist" are often "one-offs" in which the players involved are breaking new ground both aesthetically and technically. In order to be able to recognize these impulses for the topic in a timely manner, the verifiable first energy delivery of the systems must generally have taken place within a period of three and a half years from the announcement of the competition, i.e. the competition takes into account projects that have only recently been completed. However, since the competition organizer is unable to provide a subsequent evaluation of any building monitoring measures, no information or experience is available on possible operating and maintenance problems in these pilot projects.

One challenge, meanwhile, is still the broad impact. As can be seen from the submissions for the 2020 competition, slightly more than three quarters of the projects come from Germany and Switzerland, supplemented by a few entries from Austria. Since 2008, German-speaking (D-A-CH: Germany, Austria, Switzerland) countries have again dominated the Architecture Award competition, accounting for a good three-quarters of the entries;; the increase in projects from Switzerland is clearly noticeable here. Among the international entries, there is a pleasingly noteworthy range of between 20 and 30 % of the submissions, whereby the country focuses within the competitions also shift again and again. (Fig. 30) The goal for subsequent competitions is to actually attract even more participants from all over the world to take part.

For decades, building culture has been a seemingly negligible factor in the everyday life of many countries. Here, architects are the decisive professional group to further develop the numerous positive examples and to try out new approaches. This also applies in particular to building-integrated solar technology. It is therefore particularly pleasing that the orientation of the competition is confirmed among the entrants. Within the "planners" group, which also includes employees of building authorities and engineers, architects are by far the largest group with an average of 57 percent; in 2017 and 2020, numerous engineers also participated (12 and 17 percent, respectively).



Fig. 30/31: Locations of the submitted projects (left) and submitters by group of persons and industry sector (right)

In the 2020 competition, the solar industry's stronger presence in the market is also reflected in almost a quarter of the submissions. (Fig. 31)

The current challenges, such as the energy transition and the climate crisis, require creative designers and technically competent planners in equal measure. It is a matter of daring the adventure of solar architecture, worldwide at the most diverse locations and in the most diverse climatic regions (Fig. 36-39), on a qualitative as well as quantitative level. This task is supported by the "Architectural Award Building Integrated Solar Technology", which has established itself worldwide with a unique selling point in the field of the interface between architecture and solar technology, with important educational and informational work. (Krippner (ed.), 2017)

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Fig. 32/33/34/359/36/37/38/39: (first row) St. Trinitatis, Leipzig (2014), Schulz und Schulz (left) and Copenhagen International School, Nordhavn (2017), C. F. Moeller Architects (right); (second row) Mühlfeldbräu, Bad Tölz (2009), Lichtblau Architekten (left) and Aktiv-Stadthaus, Frankfurt (2015), HHS Planer + Architekten (right); (third row) Halle Pajol, Paris (2013), Jourda Architectes (legt) and 1 Bligh, Sydney (2011), Ingenhoven Architects (right); (fourth row) Saxum Vineyard Equipment Barn, Paso Robles (2018), Clayton Korte Architects (left) and PowerHYDE, Mathjalgaon (2019), Architecture Brio (right) Krippner, R., Becker, G., Flade, F., Schiebelsberger, B., Weber, W.,: Architektur und Solarenergie. Ausgezeichnete Projekte aus dem SeV-Wettbewerb "Architekturpreis - Gebäudeintegrierte Solartechnik 2014". In: 7. Forum "Bauwerkintegrierte Photovoltaik". Tagungsband. Regensburg 2015, pp. 89–95

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Evaluation of the implementation of a BIPV glass in office buildings in Spain

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Abstract

The evaluation of the impact of a transparent BIPV glass on an office building energy demands is presented for two climatic areas in Spain. The BIPV glass evaluated is a currently in development innovative technology consisting of a tandem structure of a photovoltaic active ultra-violet filter and organic infra-red photovoltaic cell. The evaluation is carried out with dynamic building simulation, using the experimental optical and electrical properties of the BIPV glass with new transparent BIPV model features. Conventional, acting as reference, and BIPV windows configurations are defined to fulfil the Spanish building code requirements. Then, the heating, cooling, and lighting energy demand, as well as the PV output are calculated, estimating the overall energy balance of the building. In terms of individual end uses, the consumption increases for heating and lighting, while decreasing for cooling. As a result, the total final energy increases in the heating dominated case and decreases in the cooling dominated. However, once accounting the PV generation the results show that the transparent BIPV glass presents an improvement of the overall energy balance by 47.2% and 17.2%, for warm and cold climatic regions in Spain, respectively.

Keywords: transparent BIPV, building simulation, emerging PV

1. Introduction

Reducing buildings' energy consumption and emissions is decisive to reduce the environmental impact and to make global economy sustainable. Currently, energy consumption in buildings represents about 40% energy and process-related carbon dioxide (CO₂) emissions (IEA, 2019), while its demand is forecasted to keep growing in the coming decades due to the floor growth increasing faster (2.5% per year) than the reduction in energy intensity (0.5-1%) since 2010 (IEA, 2020). Despite the implementation of energy efficiency measures, the service demand increase offset any improvement, resulting in an average annual energy demand increased by 1.8% in the last years (IEA,2020; UN Environment, and International Agency, 2017). This challenges the goal to reduce greenhouse gases (GHG) emissions in order to meet a 1.5°C world or below (IPCC, 2018).

Consequently, the EU implemented a legislative framework targeting buildings with the goal to achieve Europe energy and environmental goals, which included the *Energy Performance of Buildings Directive 2010/31/EU (The European Commission, 2010)* and the *Energy Efficiency Directive 2012/27/EU (The European Commission, 2021)*; both amended in 2018 and 2019, respectively. This stacks with European Green Deal presented in December 2019, which aims to make Europe the first climate-neutral continent by 2050 (The European Commission, 2020), adding to December 2018 obligation for public building to be NZEB. Reaching this goal implies improvement of the energy efficiency, but it will only be achieved considering on-site renewable energy generation. Among these, PV presents the best opportunities for energy generation adapted to buildings design, specially through Building Integrated Photovoltaics (BIPV).

© 2021. The Authors. Published by International Solar Energy Society Selection and/or peer review under responsibility of Scientific Committee doi:10.18086/swc.2021.09.02 Available at http://proceedings.ises.org BIPV are a promising solution for the buildings energy transition (Biyik et al., 2017). These technologies consist on replacing conventional building components or materials with PV active elements, keeping their aesthetical and structural functions. As crystalline silicon based cells are the most ubiquitous, due to their high performance, efficiency and availability, the most usual approaches are to replace opaque elements, either by PV modules attached to the envelope or with building elements with built-in PV cells. More recently, the emerging PV technologies as thin-film solar cells, allowed implementation in the transparent surfaces, either by cells cladding or with semi-transparent films (Jelle et al. 2012). In this sense, transparent BIPV are growing interest for implementation in building, particularly in windows, as these introduce advantages in solar gains control, daylighting, and aesthetical integration in buildings.

While transparent BIPV technologies are still dominated by Si based cells, mainly semi-transparent amorphous silicon cells, the interest on other technologies is growing. Recent development of thin film solar cells (TFSC), organic PV cells (OPV), perovskites, among others, offer new range of transparencies, shapes, cost-effectiveness and PV efficiency options (Husain et al., 2018). These features promise a great future for new architectural applications as PV windows. In order to select the adequate technology for implementing into a building, its impact on the thermal and lighting loads, as well as the electricity output and occupant comfort must be evaluated. Hence, a detailed dynamic building simulation is needed to accurately model the optical, thermal, and electrical performance of the PV glazing in conjunction with the whole building.

This study is carried within the framework of Tech4win project (Tech4win, 2019), whose objective is to develop a tandem structure of PV active UV filter and organic IR PV cell. The goal of the current study is to evaluate the performance of the last development of the BIPV tandem structure and to compare it to conventional windows in office buildings in Spain.

2. Methodology

The building simulations are run with TRNSYS18 Type 56 multi-zone building. A modified version of the Complex Fenestration System (CFS) model (Romani et al. 2021) is used. The following sections present the approach for BIPV, as well as the parameters used in the simulations evaluation.

2.1. BIPV model

The CFS implemented in TRNSYS (Hiller and Schöttl, 2014) allows the calculation of the optical and thermal behaviour of a window composed of up to six panes including external and internal shading systems. It uses ISO 15099 (ISO 15099, 2003) energy balance and bidirectional scattering distribution function (BSDF) for optical calculations. The modified version of the CFS introduces a new input allowing to introduce the PV generation into the window panes energy balance, Fig. 1. It can be assigned to the specific pane containing the PV cell. The energy is distributed equally between the two nodes (front and back) of the glazing pane.



Fig. 1 ISO 15099 window energy balance modified to include PV generation (Romaní et al., 2021).

In the current study, the output of the cell is calculated using equation 1 (Evans and Florschuetz, 1977). The inputs are obtained from CFS model outputs. The cell temperature is the average temperature of the corresponding

window pane. The radiation available in the pane is calculated with the radiation outputs according equation 2.

$$\dot{P}_{PV,i} = \eta_{ref} \left[1 + \beta_T (T_i - T_{ref}) \right] G_{\tau\alpha}$$

$$(eq. 1)$$

$$G_{\tau\alpha,i} = G_t - G_r - \sum_{i=1}^{i-1} \dot{S}_n$$

$$(eq. 2)$$

Where $\dot{P}_{PV,i}$ PV output at "i" window pane [W·m⁻²]; η_{ref} PV cell nominal efficiency [-]; β_T : Temperature coefficient [%·K⁻¹]; T_i temperature of the window pane [°C]; T_{ref} reference temperature of PV cell nominal efficiency calculation, 25 °C; $G_{\tau\alpha}$ transmitted and absorbed solar radiation at the window pane "i" [W·m⁻²]; G_t global solar radiation incident to the window [W·m⁻²]; G_r reflected solar radiation [W·m⁻²]; and \dot{S}_n absorbed solar radiation at the previous window pane "n" [W·m⁻²].

Illuminance conditions and lighting control are modelled using Type 56 integrated Daysim approach. Note this method does not use the CFS capabilities from the add-on. However, as the current study does not consider shading system no significant discrepancies are expected.

2.2. Evaluation parameters

As any window, transparent BIPV window affect the heating, cooling, and lighting loads of the building, while also adding the electricity production. The characteristics of the PV glass influence the whole window configuration, resulting in optical and thermal properties that may differ from the conventional windows solutions implemented in a specific case. Moreover, maximization of the PV generation limits the solar protection (shading) elements to be implemented on the external side of the façade. Therefore, the implementation of transparent BIPV window need to optimize the design accounting all the possible impacts on the building energy demand.

The energy performance is calculated using the final energy for cooling, heating, lighting, ventilation, and PV generation, with the overall performance being assessed by the energy balance index (EBI) as presented in equation 3. The final energy is considered electricity for all end uses, assuming heating and cooling is supplied by a reversible heat pump.

$$EBI = HFE + CFE + LFE + VFE - PV$$
 (eq. 3)

Where EBI: Energy balance index [kWh]; HFE: Heating final energy [kWh]; CFE: Cooling final energy [kWh]; LFE: Lighting final energy [kWh]; VFE: Ventilation final energy [kWh]; and PV: Photovoltaic generation [kWh].

Regarding the lighting performance, the evaluation parameters are the daylight autonomy (DA), the continuous daylight autonomy (CDA), and the hours with too high illuminance. The DA measures the fraction of occupancy hours in which the daylight illuminance in the reference point is above the minimum required illuminance (500 lux). CDA works as DA but also giving credit for the hours in which the illuminance is below the required value. Finally, illuminance above 2000 lux is considered to cause too bright environments which might lead to visual discomfort as well as glare risk.

3. Case of study

The case study consists in evaluating a sample office room in two different climatic zones in Spain. The envelope and windows characteristics are adapted to Spanish building code (Ministerio de Fomento, 2019) requirements for the selected climatic zones.

3.1. Climatic conditions

Two different climatic zones are selected for the case study, using Almeria as reference city for a warm climate and Leon as reference for a cold climate. Each corresponding to climates of types "A" and "E", respectively, according Spanish building code. The characteristic of each climate are summarized in Tab. 1.

Reference city	Almeria	León
Spanish building code classification	A4	E1
Köppen Geiger	BWk	Csb
Average temperature	18.4 °C	12.3 °C
Annual solar incident radiation on horizontal surface	1825.2 kWh/m ²	1605.1 kWh/m ²

Tab. 1: Climate characteristics.

3.2. Building characteristics

The study uses a reference room facing South with a single façade exposed to outdoors, whose geometric characteristics are summarized in Fig. 2. The same construction solutions are used in all the cases, adjusting the insulation to fit the thermal transmittance (U-value) requirement in each climate, as summarized in Tab. 2, Tab. 3, Tab. 4, and Tab. 5. Only the external wall and the roof needed adjusting the insulation, the parameters that differs between each case are highlighted.

	Parameter	Value
	Length	11.21 m
	Depth	9.58 m
	Height	3.47 m
	Floor surface	107.39 m ²
	Façade surface	33.24 m ²
	Window surface	18.48 m ²
	Window to Wall Ratio (WWR)	47.5%

Fig. 2. Reference room characteristics.

Tab. 2. Façade wall characteristics.

Faça	de wall composition and properties	Almería	León
Composition	Lacquered aluminium	0.002 m	0.002 m
_			
	Rock wool	0.050 m	0.120 m
	Galvanized steel	0.002 m	0.002 m
Total thickness		0.054 m	0.124 m
U-value		0.687 W·m ⁻² ·K ⁻¹	0.307 W·m ⁻² ·K ⁻¹

Tab. 3. Roof characteristics.

R	Roof composition and properties	Almería	León
Composition	Sand gravel	0.100 m	0.100 m
	Cellular concrete	0.125 m	0.125 m
	Cork	0.005 m	0.006 m
	Reinforced concrete slab	0.350 m	0.350 m
	Aluminium ceiling	0.005 m	0.005 m
Total thickness		0.585 m	0.586 m
U-value		0.483 W·m ⁻² ·K ⁻¹	0.327 W·m ⁻² ·K ⁻¹

Tab. 4. Floor characteristics.

Floor composition and properties		Almería	León		
Composition	Ceramic tile	0.020 m			
	Cement mortar	0.020 m			
	Sand	0.020 m			
	Reinforced concrete slab	0.035 m			
	Aluminium	0.005 m			
Total thickness		0.415 m			
U-value		2.4 W·m ⁻² ·K ⁻¹			

Tab. 5. Inner walls characteristics.

Inne	r walls composition and properties	Almería	León
Composition	Gypsum	0.030 m	

	Rock wool	0.070 m	
	Gypsum	0.030 m	
Total thickness		0.130 m	
U-value		0.440 W·m ⁻² ·K ⁻¹	

The building operates under a generic office schedule, presented in Fig. 3. The sensible heat gains and radiative fraction is summarized in Tab. 6. People and equipment gains are proportional to the occupancy profile, while lighting gains depend on the lighting control. The air renovation rates are 1.1 ACH for ventilation and 0.32 ACH for infiltration. Heating operates with a set-point of 21°C and a set-back of 17°C during non-occupancy hours. Cooling operates with a set-point of 26°C.

In terms of electricity consumption, the heating and cooling is supplied by a reversible heat pump (HP) with a COP of 3.5 and a EER 2.2. The equipment and lighting electricity specific power is presented in Tab. 6. The lighting is controlled under a continuous daylighting strategy, in which the lights are continuously dimmed up to 500 lux of daylighting. The reference sensor is place at the centre of the room at 0.85 m from the floor. Finally, ventilation electricity consumption is calculated with a linear correlation of 2 kW per $m^3 \cdot s^{-1}$.



Fig. 3. Occupancy schedule.

Tab. 6. Internal heat gains and associated specific power.

Gain type	Sensible heat gain	Radiative fraction	Specific power
People	6 W·m ⁻²	0.2	-
Equipment	4.5 W⋅m ⁻²	0.5	5.63 W·m ⁻²
Light	4.11 W⋅m ⁻²	0.42	7.28 W·m ⁻²

3.3. BIPV window characteristics

Regarding the windows, the conventional solutions in Spain consist of double glazing with air-chamber, including low-emissivity glass in the colder climates. The BIPV solutions use the same structure but removing the outermost clear glass with the currently in development Tech4win transparent BIPV glass, which consists of a tandem structure of a photovoltaic active UV filter and IR organic photovoltaic cell. Both cases consider a 15% frame of insulated PVC with thermal break.

The conventional window is modelled using the glass data from the International Glazing Data Base (IGDB) (Lawrence Berkeley Laboratory, 2021a) included in WINDOW7 (Lawrence Berkeley Laboratory, 2021b). For the BIPV, the spectral properties were processed with OPTICS6 (Lawrence Berkeley Laboratory, 2013). Note that the BIPV glass has properties similar to a solar control glass, as shown in Fig. 4, although with lower visible transmittance and higher absorption in the UV and near infrared related to the PV cell properties.

The properties of the conventional and BIPV window for both scenarios is summarized in Tab. 7 and Tab. 8. The thermal transmittance (U-value) of both cases is similar, which fits with the Spanish building code prescriptive requirements (Ministerio de Fomento, 2019), 2.7 W·m⁻²·K⁻¹ and 1.8 W·m⁻²·K⁻¹ for Almería and León cases, respectively. However, the optical properties of the BIPV window, with higher absorption leads to a lower solar heat gain coefficient (SHGC) and visible transmittance (τ_{vis}). The BIPV is modelled with a nominal efficiency of (η_{ref}) 5.54 % and a temperature coefficient of (β_T) of -0.25 %/K. This is the most up to date efficiency data obtained in Tech4win laboratory scale devices. Finally, the case study does not consider shading systems, neither external nor internal.


Fig. 4: Comparison of glass transmittance

Tab. 7: Window configuration for CTE climate "A" requirements (Almería)

Case	Glazing system	U (W·m ⁻² ·K ⁻ 1)	SHGC (-)	τ _{vis} (-)
Conventional	8/12/8 (float glass / air / float glass)	2.553	0.587	0.544
BIPV	14/12/6 (BIPV glass / air / float glass)	2.550	0.352	0.276

Tab. 8: Window configuration for CTE climate "E" requirements (León)

Case	Glazing system	U (W·m ⁻² ·K ⁻ 1)	SHGC (-)	τ _{vis} (-)
Conventional	8/12/8 (float glass / air / low-e glass)	1.653	0.492	0.526
BIPV	14/12/6 (BIPV glass / air / low-e glass)	1.652	0.285	0.271

4. Results

The behaviour of the office building in representative days of winter and summer is presented in Fig. 5 and Fig. 6 for Almería and León, respectively. In both cases the BIPV window maintains a lower temperature of the room (T_{room}) in summer and winter. The lower SHGC coupled with the PV effect on the BIPV window results in a reduced window temperature $(T_{wind int.})$ compared to the conventional one, reducing the convective and long-wave radiation heat gains to the room, as well as reducing the solar gains. This impact is higher in winter than in summer, as the heating load is driven by outdoor climatic conditions while the cooling load is mainly driven by internal gains. As a result, in the BIPV window case the heating load increases and the cooling load decreases. Moreover, the reduced window temperature and solar heat gains results into a lower radiant temperature (T_{rad}), up to 2°C in winter and up to 1°C in summer. The difference in radiant temperature will affect to the thermal comfort of occupants, although the analysis of this issue is beyond the scope of the current paper.

Regarding the lighting performance, the lower visible transmittance of the BIPV window reduces the natural daylight illuminance on the reference sensor. This helps in having fewer hours of excessive illuminance (>2000 lux), especially in the winter days when the sun elevation is lower. However, it also implies more time in which the daylight illuminance is below the set-point of 500 lux, then lighting is ON for more hours and with higher power required (Light control). In the southernmost climate of Almería with high sun elevation all year round, the BIPV window guarantees that daylight illuminance does not exceed 2000 lux at the reference sensor. In contrast, in Leon the low sun elevation in winter causes very high daylight illuminance, although high values still happen.



Fig. 5. Almería representative days for winter (left) and summer (right)

The different behaviour of the BIPV and conventional window results in the electricity consumption summarized in Tab. 9, Fig. 7 and Fig. 8. The change of electricity consumption for each end use ranges from 32% (heating in León) up to 155% (lighting in Almería). However, it is their relative weight in the total energy consumption that defines the impact on the energy balance. In the warm climate of Almería scenario, the reduction in cooling (4.79 kWh) compensates the increase of heating and lighting (4.1 kWh), with the total final energy decreasing -3.6%. In contrast, in the colder climate in León the reduction of cooling (-2.28 kWh) does not compensate the increase in heating and lighting (6.06 kWh), with the total final energy increasing 16.2%. Nevertheless, once the PV output is considered in the energy balance, the BIPV window improves the results of the conventional one in both scenarios.



Fig. 6. León representative days for winter (left) and summer (right)

Case		Ventilation	Lighting	Cooling	Heating Total		PV	EBI
Almeria	REF	5.44	1.55	11.34	1.25	19.59	0.00	19.59
	BIPV	5.44	3.97 6.55		2.93	2.93 18.88		10.34
		(0.0%)	(+155.2%)	(-42.3%)	(+133.3%)	(-3.6%)		(-47.2 %)
León	REF	5.44	2.91	4.22	10.80	23.36	0.00	23.36
Ĩ	BIPV	5.44	5.47	1.94	14.30	27.15	7.80	19.35
		(0.0%)	(+87.8%)	(-54.0%)	(+32.4%)	(+16.2%)		(-17.2%)

Tab. 9: Annual final energy results [kWh·m⁻²]

The monthly distribution, Fig. 7 and Fig. 8, shows that the highest difference in lighting consumption happens in summer, when the conventional window can best exploit the daylight during all occupancy hours. Regarding the PV output, the production in summer can be used for self-consumption easier than in summer, as the occupancy (equipment loads) and the cooling load match the PV output. In contrast, winter loads are concentrated in early morning and late afternoon, resulting in a higher fraction of exported electricity. Finally, the vertical position and South facing of the PV panels in the case studies result in higher electrical outputs in winter than in summer.



Fig. 7: Almeria monthly final energy (left column for RF and right for PV).



Fig. 8: Leon monthly final energy (left column for RF and right for PV).

As seen in the lighting consumption, the PV window has a negative impact in the daylighting of the building due to its lower τ_{vis} . This results in a significant decrease of the daylighting autonomy and continuous daylighting autonomy, as summarized in Tab. 10. However, the PV window significantly reduces the time with excessive illuminance, by 100% and 67.4% for Almería and León, respectively.

5. Discussion

The results highlight the complex assessment of implementing transparent BIPV as replacement for conventional fenestration systems. Its impacts on the heating, cooling, and lighting consumption need to be evaluated, as well as the design to maximise the PV production. The optical properties of the BIPV glazing may have favourable impact on the building performance in hot sunny climates, with a low SHGC and τ_{vis} to regulate the cooling loads. However, it can have a negative impact on the heating loads, as it reduces the solar heat gains, and lighting, due to a usually lower τ_{vis} . This analysis becomes more complex once the building envelope design is considered. In the current study a single façade solution is used for both the conventional and BIPV glazing system, in both cases disregarding any shading system and/or double skin configuration. As an example, an external shading system could reduce the cooling load and excessive illuminance hours with a conventional glazing, but it cannot be used with transparent BIPV if PV generation is to be maximized. Moreover, the BIPV window impacts on the radiant

temperature of the room, hence to the thermal comfort of occupants. Consequently, the results showcase the need to implement an integrated simulation. The methodology presented allows to model the BIPV performance together with the building heating, cooling, lighting, and ventilation loads using a modified version of TRNSYS Type56 Complex Fenestration System (CFS) add-on.

		A	Imeria	Le	ón	
Ca	ise	REF	BIPV	REF	BIPV	
	Jan	80%	72%	62%	52%	
	Feb	85%	74%	75%	62%	
	Mar	93%	79%	84%	69%	
	Apr	99%	83%	91%	72%	
	May	99%	77% 9		75%	
CDA	Jun	100%	82%	95%	78%	
CDA	Jul	100%	81%	97%	80%	
	Aug	99%	83%	96%	78%	
	Sep	96%	81%	95%	83%	
	Oct	91%	81%	80%	66%	
	Nov	82%	74%	69%	58%	
	Dec	72%	64%	66%	58%	
Annual CDA		91%	78%	84%	69%	
Annual DA		85%	46%	71%	40%	
Annual III > 2000 lux [h]		300.7	0.0	292.2	95.0	

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The results of the currently in development Tech4win BIPV glass have promising results for reducing the energy consumption of office buildings in Spain, according to the considered case studies. In the warm and sunny case of Almería, the final energy use decreases by 3.6% with the overall energy balance decreasing by 47.2% due to the PV energy production. In the colder León case, the final energy use increases by 16.2% mainly due to worst heating and lighting performance, although the PV generation offsets this increase leading to a reduction of the overall energy balance by 17.2%. Nevertheless, the current study does not consider the optimization of the conventional windows for each case study, only looking to comply with Spanish building code. However, using a solar control window in the Almería scenario will improve the reference case performance, reducing the savings related to the BIPV window. Therefore, the optimal building envelope design will change depending on the glazing solution, affecting the overall energy balance which will also affect the economic feasibility.

Finally, the current study is based on data of a BIPV glass still in development. The PV efficiency considered is taken from measurements on laboratory scale devices, as data from up scaled large size modules is not yet available. As reference, CIGS technology consistently achieves cell efficiencies around 20%, but development of modules showed efficiencies stagnating at 14-15% (losses above 25%) (Bermúdez and Pérez-Rodríguez, 2018). However, the losses of the new tandem technology are unknown, their assessment still on-going. Fig. 9 shows an estimation of the impact on the energy balance of the reduced PV efficiencies from the cell levels values. In the Almería case, even minimal efficiencies will lead to an improvement in the energy balance. On the contrary, in León case the solar control properties of the BIPV window are not desirable, meaning a minimum level of efficiency, around 3%, needs to be guaranteed in order to improve the energy balance. Nevertheless, it is reasonable to assume higher investment cost of BIPV windows, hence, the reduction in operation cost within the lifetime needs to offset the increase in capital costs.



Fig. 9. BIPV window energy balance comparison at different PV efficiencies in Almería (left) and Leon (right) cases.

6. Conclusions

An evaluation of the implementation of the transparent PV glazing developed in Tech4win project in Spanish office building is presented. The research is based in the latest experimental optical and electrical performance data on laboratory devices. The simulation is carried out with a modified version of TRNSYS Type 56 Complex Fenestration System, allowing and integrated evaluation of the impact on the heating, cooling, lighting, and PV generation loads.

The results showed that the transparent BIPV glazing can reduce the overall energy balance of office buildings in Spain. The optical characteristics gives the BIPV glazing solar control properties, which improves the performance of building in sunny warm climates by reducing cooling demand, although these characteristics increase the heating demand in cold climates. Additionally, the BIPV window increases the lighting demand due to lower visible transparency, although it also reduces the visual discomfort risk. Nevertheless, the currently available efficiency data leads to overall energy savings in the two cases considered. However, the envelope design needs to be optimized for both the conventional and BIPV glazing including the shading system management in order to have a comprehensive evaluation of the best solution in every specific case.

Further work will include economic evaluation with estimation of the BIPV window cost and the impact of variable electricity prices, as well as extension to other climatic regions. Moreover, the impacts on visual and thermal comfort, with improvement of the daylighting calculations will be assessed.

7. Acknowledgements

This work has received funding from the European Union H2020 Framework Programme under Grant Agreement no. 826002 (Tech4Win). Joaquim Romaní would like to thank Ministerio de Economia y Competitividad de España for Grant Juan de la Cierva FJC2018-038475-I.

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Comparison of Seventeen Models to Estimate Diffused Solar Radiations on a Tilted Surface

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Abstract

This study aims to evaluate daily diffused solar irradiance from a horizontal to a tilted surface using 17 different sky models based on a variety of different sky conditions. The selected sky models are classified into two categories namely isotropic and anisotropic, based on assumptions made to define behavior of diffused radiations all over sky dome. Solar radiations falling on a tilted surface are computed and compared for two stations Lahore and Khuzdar based on their respective clearness indices. Solar radiation data for period of one year (Jan 2016 – Dec 2016), was used to evaluate the sky models. The daily surface albedo was computed from hourly albedo from MERRA-2 to estimate reflected component of radiations. The calculations were based on daily measured global irradiance for horizontal surface. Beam, diffused and reflected components of radiation on the tilted surface were computed with tilt angle variation from 0° to 90°. The maximum mean annual radiations for Khuzdar with the highest sky clearness index (K_T) and Lahore with lowest K_T among selected stations were found to be 326 W/m² and 209 W/m² respectively. The daily optimum tilt angle corresponding to the maximum annual radiations varies from 0 to 75° throughout the year. The respective average maximum total solar radiation for optimum annual tilt is 190 W/m² and 289 W/m² for Lahore and Khuzdar respectively. A comparison of different models shows almost 6 to 11% increase in mean monthly total radiations with monthly optimum tilt as compared to latitude tilt for both Lahore and Khuzdar.

Keywords: Optimal tilt angle, Solar radiations, Isotropic models, Anisotropic models

1. Introduction

Renewable energy has evolved as a global fast-growing trend to fulfill increasing energy demands around the globe due to its environment friendly nature and sustainable production of energy. A variety of renewable energy resources (Solar, Wind, Geothermal etc.) are being used as an alternative to non-sustainable resources like coal. However, a substantial increase in the use of solar energy has made it the fastest growing energy source among all other renewable energy resources. Solar energy is standing out as an important integrated energy source to meet the current energy needs partly due to its easy deployment on both smaller and larger scales (Li et al., 2015). Solar energy is being utilized through both active (direct conversion of solar energy to electrical energy) and passive (indirect use of solar energy for water heating, cooking, etc.) technologies. Solar PVs, flat plate collectors, and concentrated solar panels are a few examples of modern active solar conversion technologies used these days. However, the lower efficiency of solar energy conversion devices is one of the major concerns associated with the commercial application of these devices. The design of such devices requires the optimal installation parameters to enhance their performance.

The performance of solar energy conversion devices is a function of surface orientation with respect to the sun; the azimuth angle (γ) and the surface inclination or tilt angle (β). Hence, both the orientation and tilt of the solar PV quantify the amount of solar radiations falling on an inclined surface of a panel (Kaddoura et al., 2016). The solar PVs are often installed as a fixed unit with a certain amount of tilt while the sun covers a unique path as the day passes. The application of solar tracking system is the best possible way to maximize the incident solar radiations by adjusting the position of solar PV to face the sun path throughout the day. A Single Axis Solar Tracking (SAST) system can achieve up to 18% higher solar energy compared to a fixed collector (Batayneh et al., 2019). While, an increase of about 13-15% in the daily power output of PV arrays is observed with the application of a dual-axis tracking system (Şenpinar and Cebeci, 2012). However, the hefty costs of the solar tracking systems put a limitation to its application especially for the smaller scale systems. The amount of global radiations falling on the Earth surface varies with the climatic conditions,

seasonal changes and latitude of a location affecting the performance of solar PV modules (Huld et al., 2012). A reasonable increase in the performance of solar PV modules can be achieved by using an optimal monthly, seasonally and annual tilt angle. Khoranizadeh et al. (Khorasanizadeh et al., 2014) reported an effective 22% and 23% increment in the harnessed energy by using optimal tilt of solar PV on seasonal and monthly basis. While, 14% energy enhancement can be achieved by adjusting the Solar PV on semi-yearly basis.

The data for global and diffused solar radiations are measured on a horizontal surface. The conversion of available radiation data for the horizontal surface to the tilted surface is a prerequisite to estimate the required optimal tilt angle (Demain et al., 2013)The total solar radiations (H_T) reaching the Earth is composed of three major components; beam or direct radiations (H_B), diffused (H_D), and reflected radiations (H_R). Diffused radiations get scattered due to the presence of aerosols or clouds in the atmosphere. While, the reflected radiation is the component of total radiations which is reflected through different surfaces (Drummond, 1956). The approximation of total tilted radiation is the sum of tilted beam, reflected, and diffused radiations which are calculated separately. The estimation of beam component on tilted surface is often simple as it involves geometric relation (R_b) which represents the ratio of beam radiations between the tilted and horizontal surface (Huld et al., 2012). For the diffused part of the radiation, availability of the measured data for different locations is difficult to estimate, as the diffused component is a complex function of humidity, turbidity, clearness index, sky condition, humidity, and many other atmospheric and meteorological conditions in addition to the geometric factor (Duffie and Beckman, 1980)

Several different models have been presented by different researchers to estimate the diffused component on tilted surface. The formulations of these models are based on the sunshine hours, sky clearness index (K_T), relative humidity (R_h), and other meteorological factors (Jamil et al., 2017). These models based on their unique method to address the diffused radiations, are classified as the isotropic and anisotropic models. Isotropic models present simplified methodology to estimate the diffused radiations by assuming the isotropic scattering of radiations throughout the sky dome. While, the anisotropic models include detailed insights considering both isotropic and anisotropic parts of the diffused radiations. Reindl et al. (Reindl et al., 1990) proposed studied a set of 28 significant factors and selected four significant factors after reduction to present his model the model was based isotropic (all over the sky dome) and anisotropic (around the Sun disc and horizon) part of the diffused radiation of diffused radiation data on tilted surface. The chosen twelve models were examined for the west and south facing irradiances at Karaj ($35^{\circ}55'$ N; $50^{\circ}56'$ E) Iran. The methodology used by all these models was almost same for the estimation for beam and reflected component whereas different techniques were suggested for the estimation of diffused component.

This study presents the evaluation of isotropic and anisotropic sky models to maximize the solar radiations. The chosen isotropic models include Liu and Jordan Model (LJ), Koronakis Model (Kr), Bdescu Model (Ba) and Tian Model (Ti). While anisotropic models include Skarvieth and Olseth model (SO), Wilmott model (Wi), Perez Model (Pr), Hay Model (Ha), Steven and Unsworth Model (SU), Ma Iqbal Model (Iq), Reindl Model (Re), Bugler Model (Bu), Muneer Model (Mu), Klucher Model (Kl), Ma Iqbal Modified Model (IM), Temps Coulson Model (TC) and Gueymard Model (Gu). These sky diffuse models are used in estimation of diffuse component of radiations on tilted surface by varying the tilt angle from 0 to 90°. The models that estimates the maximum amount of solar radiations on tilted surface is recommended for the given latitude.

2. Solar Radiations Data

The measured solar radiations data for the present analysis was obtained through the Energy Sector and Management Assistance Program (ESMAP) of the World Bank. The data of Global Horizontal Irradiance (H_g), Beam irradiance (H_b), Diffused horizontal irradiance (H_d), for the stations Lahore and Khuzdar were used for the period of one year (January 1, 2016 – December 31, 2016). The data of H_g , H_b , and H_d for Lahore and Khuzdar were measured through the Tier 2 system equipped with CSP services Twin-Sensor Rotating Shadow-band Irradiometer (RSI). Measurement of ambient temperature and relative humidity was carried out through Campbell Scientific CS 215. Pre-calibration of RSI sensor against a high precision instrument, for two months, was carried out by German Aerospace Center (DLR) at Plataforma Solar de Almeria (PSA) (Kraas et al., 2015). The observed annual sum uncertainty for measurement of H_g , H_b , and H_d was reported to be less than 2 %. While the uncertainty associated with instantaneous measurement of H_g , H_d and H_b was less than 4%, 6%, and

4 % respectively using CSPS RSI (Services, 2019). The daily and weekly cleaning of irradiance sensors for Tier 2 systems along with the semi-yearly inspection was also performed by a local partner of ESMAP. The daily data retrieval was done by CSP services via GPS data transmission (Stökler et al., 2016). The data quality check was carried out in accordance with the guidelines given by Baseline Surface Radiation Network (BSRN) (Li et al., 2010). Three data quality checks were applied to remove outliers in the measured data. The first quality check was based on the minimum and maximum Physical Possible Limits (PPL) as given in equations (1a) and (1b). Where, G_{sc} represents the solar constant having a value of 1367W/m² and G_e is the distance between the Sun and the Earth. The second data check involved the implementation of Extremely Rare Limits (ERL) for which the minimum and maximum values are given in equations (1c) and (1d). A third quality check was based on the comparison ratio of measured H_g and H_d data was performed across the dataset as given in equations (1e) and (1f). The data quality check was applied for the 10 minutes of data temporal resolution. The data set qualifying all of the mentioned quality checks were considered for the analysis to measure the daily mean values of global and diffused radiations while the rest of data was flagged. The period of day measuring the H_b above 120W/m² was marked as sunshine duration (Gueymard, 1993) as per the guidelines of World Meteorological Organization (WMO) to estimate the daily sunshine duration from measured H_b

H_g	$> -4 W/m^2$	(eq. 1a)
	(G_{sc}) $((G_{sc}))$ (12) (100)	(ag. 1h)

$$H_g < 1.5 \left(\frac{1}{G_e}\right) \left((\cos \theta_z)^{1.2} \right) + 100$$
 (eq. 16)

$$H_g > -2 W/m^2$$
 (eq. 1c)
 $H_g < 1.2 \left(\frac{G_{sc}}{G_o}\right) ((\cos \theta_z)^{1.2}) + 50$ (eq. 1d)

$$\frac{H_d}{H_g} < 1.05$$
 $H_g > 50 W/m^2$, $\theta_{sza} < 75^\circ$ (eq. 1e)

$$\frac{H_d}{H_g} < 1.1$$
 $H_g > 50 W/m^2$, $75^\circ < \theta_{sza} < 93$ (eq. 1f)

Qasim et. al. (Qasim et al., 2014) suggested the classification of Pakistan's regions into five different zones (A to E) based on climatic conditions and geographical characteristics. These zones are classified based on K_T . This represents the ratio of H_g to H_o . Based on the ranges of cloud clearness index, the cloud conditions are classified into three categories: $0.65 < K_T \le 1$ for clear sky condition, $0.3 < {}_{T}K_T \le 0.65$ for partial cloud cover, and cloudy sky for $0 < K_T \le 0.3$. The present study focuses on the analysis of two stations selected from different zones. Lahore with a clearness index value (K_T) of 0.49, belongs to zone B depicting intermediate sky conditions while Khuzdar having a clearness index (K_T) of 0.68 belongs to Zone C having clear sky conditions. The meteorological and geographical details for the selected stations are shown in Tab. 1.

Tab.1. Meteorological and Geographical Details of the Selected Stations

Stations	Station Code	Zone	Latitude	Longitude	$\mathbf{H}_{\mathbf{g}}$	$\mathbf{H}_{\mathbf{d}}$	Ν	Т	R _H	K _T	KD
			°N	°E	Wm ⁻²	Wm ⁻²	(hours)	°C	(%)		
Lahore	LHE	В	31.694	74.244	180	93	7.2	24.8	71.1	0.49	0.57
Khuzdar	KHZ	С	27.8178	66.6294	250	82	9.4	23.8	30	0.68	0.33



Fig. 1. Monthly Average Daily Global Horizontal and Extraterrestrial Radiations for (a) Lahore (b) Khuzdar

In Pakistan, May, June, and July are marked as the hottest months during the summer season with the longest sunshine. As the global irradiance depends upon the sunshine duration and the prevailing temperature of the region, the highest values of global irradiance for the site of Lahore and Khuzdar is observed during the months of May and June respectively as shown in Fig. 1. A slight decline for the month of July was observed as the duration of sunshine comparatively becomes shorter. The peak value of H_g is 252.1057W/m² for Lahore and 312.4451W/m² for Khuzdar correspond to the month of May. The minimum values of global irradiance correspond to the months of November and December due to comparatively fewer sunshine hours and lower atmospheric temperature.



Fig. 2. Monthly Average Daily Global, Beam and Diffused Radiations for (a) Lahore and (b) Khuzdar

Fig. 2 gives the distribution of measured H_d with respect to the global horizontal irradiance throughout different the year. The intensity H_b is directly affected by the sunshine hours. In Lahore the peak values of beam radiations were found to be 152.2217 W/m² and 141.5594 W/m² for April and May respectively due to the plenty of available sunshine duration.

3. Methodology

The total solar radiations approaching the Earth were modeled as given by Eq. (2) and classified into three components; Beam or direct (H_B), Reflected (H_R) and the diffused (H_D) components of the radiations on a tilted surface. The radiations incident directly on the surface of solar PVs without any deviation are termed as beam radiations. The radiations received by the panel's surface after being reflected due to the phenomena of surface albedo are referred to as the reflected radiations while the radiations scattered into the atmosphere due to the clouds or suspended particles in the atmosphere are known as diffused radiations.

$$H_T = (H_g - H_d) \times R_b + H_d R_d + 0.5 H_g \times (1 + \cos\beta)$$
(eq. 2)

The reflected radiations on an inclined surface (H_R) were expressed in terms of global horizontal radiations (H_g) and surface albedo (ρ) in Eq. (2). Generally, a standard fixed value of 0.2 is widely used for the surface albedo. However, in the given case considering the fact that albedo for a natural surface keeps on varying, Eq.

(2) is fed with data set of hourly variation in the surface albedo acquired from MERRA-2. The daily average albedo which was estimated by utilizing the available data for hourly variation in the ground albedo was further used for the calculation of the average daily reflected radiations falling on the collector surface.

 R_d represents the ratio of diffused radiations on inclined surface to the horizontal surface in Eq. (2). As the amount of diffused radiations depends upon a number of variable factors, R_d can be expressed as the function of different sky models corresponding to various sky conditions. Seventeen different sky models were selected from the literature to estimate R_d .

3.1 Isotropic sky models

Isotropic models are entirely focused on the isotropic part of the radiations as they are based on the assumption that scattering of radiations is constant over the sky dome. A detailed description of selected isotropic models is discussed in this section.

Liu and Jordan (Liu and Jordan, 1963)presented the simplest isotropic model for the estimation of empirical data for the cloudy skies. In circumsolar and horizon brightening were taken as zero. This model tends to perform well under the cloudy sky conditions as compared to the clear sky conditions. *Koronakis model* (Koronakis, 1986) with a few corrections to Liu and Jordan Model, was proposed in 1986. This improved version of Liu and Jordan Model enhanced the calculation accuracy for regions in Northern Hemisphere. *Badescu model* (Badescu, 2002) is also an advanced version of Liu and Jordan Model. This model defines the zenith angle and azimuth angle on the basis of 3D theory contrary to the Liu and Jordan Model that defines the zenith angle using the 2D theory. *Tian Model* (Tian et al., 2001) gives the approximation of diffused radiations striking the tilted surface while differentiating them from the global radiations. One of the positive aspects of Tian model is that it addresses the practical methods to link up total solar radiations incident on a surface to the atmospheric conditions.

3.2 Anisotropic sky models

The anisotropic models are based on the improved techniques which give the deep insights to analyze the diffused component of the solar radiations. The anisotropic models classified the distribution of the diffused solar radiations into two parts: the anisotropic scattering of diffused radiations around the Sun and the isotropic dispersion of the diffused radiations through rest of the sky dome.

Skartveit and Olseth Model (Skartveit and Olseth, 1986) estimate the beam and diffused components of the radiation on a tilted surface by utilizing the average monthly radiation data. It performs equally good with the constant albedo as well as the isotropic and seasonally varying albedo. For the case $H_b/H_o \ge 0.15$, corresponding to correction factor (Z) is 0, model tends to reduce to the Hay Model. Hay Model (Hay, 1979) only focused on the anisotropic distribution of diffused radiations and the anisotropic scattering in the rest of the sky region while ignoring the factor of horizon brightening. The circumsolar diffused radiations were estimated by using an anisotropic index F_{Hay} . Whereas, F_{Hay} is represented as the ratio of H_b to H_o . Hay model reduces to Liu and Jordan Model for the case $F_{Hay} = 0$. Reindl et al. Model (Reindl et al., 1990) covered the anisotropic radiations around the Sun (circumsolar), isotropic radiations and the horizontal brightening. The circumsolar radiations: the scattering of diffused radiations around the Sun due to the suspended particles and the horizontal brightening and increased scattering of the diffused radiations near the horizon due to multiple reflections only occur in the clear sky. Due to this fact, both of these phenomena were not addressed in Liu and Jordan Model. Steven and Unsworth Model (Steven and Unsworth, 1980) calculates the diffuse coefficient by considering the radiations from both horizon brightening and sun's disk. Willmot Model (Willmott, 1982) introduces an anisotropic reduction factor for the inclined surface C_{β} . Gueymard (Gueymard, 1987) proposed to calculate the radiance of a partly cloudy sky as a weighted sum of the clear and overcast sky radiance as given by Eq. (3). Ng represents the Gueymard's weighting factor for cloud opacity. Since the cloudiness data is generally unavailable, Gueymard based the function N_g on solar radiation data: The clear sky radiation, R_{d0} , is given by a polynomial regression function of the solar altitude (or elevation angle), γ and β . The overcast sky radiation, R_{d1} , is defined as a function of β in radians.

Ma Iqbal Model (Iqbal, 2012) classifies the diffused radiations into two categories: the circumsolar diffused radiations and the radiations from rest of the sky zone. Atmospheric clearness index (K_T) was used to determine

the extent of cloudiness. Eq. (4) gives the mathematical expression for the model. Ma Iqbal Modified Model (Iqbal, 2012; Steven and Unsworth, 1980) replaces the K_T with the modified clearness sky index K'_T . The modified clearness index allowed the computation without involving the solar zenith angle. Muneer Model (Muneer, 2007) estimated the intensity of diffuse radiation as given in Eq. (5). Whereas F_M is a composite clearness function depending on the particular sky and azimuthal conditions. For shaded surfaces and sunfacing surfaces under overcast sky conditions F_M is zero, while F_M is equal to F_{Hay} for clear sky and partly cloudy sky conditions. The tilt factor, T_M , represents the ratio of the slope background diffuse irradiance to the horizontal diffuse irradiance. Assuming clear sky conditions, Temps-Coulson (Temps and Coulson, 1977) modified the isotropic model by introducing two terms evaluating the diffuse radiation coming from the vicinity of the Sun's disc (P1) and the sky radiation from the region close to the horizon (P2) shown by Eq. (6). Klucher Model (Klucher, 1979) is the redefinition of Temps Coulson model by inserting a function f_k to determine the degree of cloud cover. The isotropic models which could only perform well under the overcast sky conditions, usually underestimate the irradiance under partly cloudy or clear sky conditions due to the concentrated intensity near the circumsolar region and horizon. The use of cloud cover degree was suitable to overcome such conditions. The Klucher model simplifies to the Liu-Jordan model when $f_k = 0$ or $H_d/H_g=1$ and reduces to Temps Coulson Model for $f_k = 1$ or $H_d/H_g=0$. Perez Model (Perez et al., 1990) as compared to other discussed models, uses the empirically derived coefficients to provide detailed insight for the analysis of circumsolar, isotropic and horizon brightening diffused radiations. The mathematical formulation of Perez model is given by Eq. (7). The brightness coefficients, F_1 and F_2 represent the radiations around the Sun and the region near the horizon respectively. Perez model reduces to Liu and Jordan model for the case $F_1 = F_2 = 0$. Bugler Model (Bugler, 1977) modified the isotropic model by adding terms for the diffuse radiation coming from the Sun's disc and for the radiation from the rest of the sky that depends on the angular height of the Sun over the horizon.

$$R_d = (1 - N_g) R_{d0} + N_g R_{d1}$$
 (eq. 3)

$$R_d = K_T R_b + (1 - K_T) \left(\frac{1 + \cos\beta}{2}\right)$$
 (eq. 4)

$$R_{d} = T_{M} (1 - F_{M}) + F_{M} r_{b}$$
 (eq. 5)

$$R_d = \left(\frac{1+\cos\beta}{2}\right) P_1 P_2 \tag{eq. 6}$$

$$R_d = (F_1 \frac{a}{b} + (1 - F_1) \frac{1}{\cos\theta_{sza}} \left(\frac{1 + \cos\beta}{2}\right) + F_2 \sin\beta) \qquad (eq. 7)$$

A MATLAB script was developed to find the total amount of radiations falling on the tilted surface using the discussed models. Measured solar radiations data for horizontal surface was used in a MATLAB script. In the script the input tilt angle is varied from 0-90° with interval of 1° for each day of year. The angle corresponding to which the daily H_T was maximum is termed as the daily optimum tilt angle. The monthly optimum tilt angle was found by varying the input tilt angle from 0° to 90° with an interval of 1° and corresponding total monthly average daily radiations were calculated at each angle. The angle at which total monthly average daily radiations are maximum gives the monthly optimum tilt angle of PV panel.

4. Results and Discussion

A comparison of all seventeen models was made from which a group including three isotropic models; Liu and Jordan Model, Koronakis Model and Badescu Model and three anisotropic models; Hay, MA Iqbal Modified and Gueymard models were selected based on their performance. The Gueymard model best estimated the diffused radiations for both of the selected sites. the mean annual irradiance on an inclined plane for Lahore with lowest sky K_T is 209.525 W/m² and 190.036 W/m² for daily optimum angle and annual optimum tilt angle respectively, and 326.054 W/m² and 288.88 W/m² for Khuzdar with highest K_T . Almost 16.67% increase in total annual mean irradiance on a tilted surface was observed compared to global horizontal irradiance (H_g) using the Gueymard diffuse model for Lahore. The same analysis for Khuzdar revealed that there is more than a 30 % increase in total annual mean irradiance on a tilted surface compared to H_g on a fixed horizontal surface. Among isotropic models, the Badescu showed the minimum value of total mean annual irradiance.

The total mean annual irradiance on tilted surface for Khuzdar was higher compared to Lahore. Hence, with increase in K_T , each given model best estimates the total irradiance on tilted surface. Anisotropic models show high estimation of total irradiance compared to isotropic models A comparison of the best performing anisotropic models shows that the variations in Hay model are closer to isotropic models. Also, the Gueymard model best estimates total irradiance on tilted surface among all isotropic and anisotropic diffuse models.

In winter due to the high θ_z , the inclination comes out to be greater than 10° to attain maximum solar irradiance, while in summer the daily optimum tilt angle was nearly zero. The daily optimum tilt angle ranges from 0-75° for Khuzdar and Lahore respectively. It was observed that anisotropic models were based on more accurate assumptions for sky conditions as maximum total irradiance was estimated for these models. Due to the greater K_T , Khuzdar witnessed a greater amount of incidence radiations. Further analysis showed that increase in total irradiance on the tilted surface relative to the H_g was strongly dependent upon the K_T . The correlation coefficients for the above-mentioned models were calculated. A high value of 0.913 with positive coefficient of correlation was obtained. This value was pertinent to the fact that a station with a greater value of mean annual K_T will result in an increase in total irradiance on the tilted surface relative to the H_g for a particular station. Also, the ratio of total radiations falling on the tilted surface is nearly 1.2 and 1.3 times of H_g for Lahore and Khuzdar respectively.

Gueymard model was observed to best estimate the total mean annual irradiance on tilted surface, while M.A Iqbal model dominated Gueymard model in winter month. The monthly mean daily total irradiance falling on the surface of PV panel corresponding to daily optimum tilt angle for isotropic and anisotropic models is shown in Fig. 3. A comparison among isotropic models and anisotropic models for monthly mean daily irradiance showed that anisotropic models estimate the high value of total solar irradiance on tilted surface. Among anisotropic models Gueymard model best estimate the total irradiance on a tilted surface with maximum solar radiations during the summer month. In winter solastic, Iqbal Modified model gives a promising estimation due to its modified K_T . Fig. 4 shows the monthly mean daily irradiance for latitude tilt. It was observed that the magnitude of monthly mean daily irradiance in any month corresponding to daily optimum tilt angle is higher than one estimated against latitude tilt.

Different values of H_T are found for various tilt angles in different months of the year. The angle at which the H_T reaches its maximum value refers to an optimal tilt angle. The optimum tilt angle for each month was different for each model. Monthly optimum tilt angles were computed using maximum monthly mean daily irradiance and was found that the monthly optimum angle for Khuzdar varies from 0° in June to 68° in July. The tilt angle was maximum in December month for every station. Depending upon the sky conditions and K_T the radiations incident on tilted surface were different, the maximum radiations were observed for Khuzdar with magnitude of 326.5028 W/m² in December. The minimum monthly optimum angle occurred in June for every station. The minimum radiations corresponding to the minimal optimum tilt angle occur for Lahore station having magnitude of 249.5495 W/m². It was also observed that the yearly average of daily optimum tilt angle for Lahore and Khuzdar, is 27.14° and 28.58° respectively, and the latitudes of the sites are 31.6° and 27.8°.



Fig. 3. Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Daily Optimum Tilt Angles for Khuzdar



Fig. 4. Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Latitude Fixed Tilt Angles for Khuzdar





Fig. 5. Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Daily Optimum Tilt Angles for Lahore



Fig. 6. Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Latitude Fixed Tilt Angles for Lahore

Fig.5 and Fig.6 present the comparison of monthly mean daily irradiance against the combination of selected six models for the monthly and latitude-based optimum tilt angle for Lahore. Gueymard model gives the maximum mean annual solar radiation of 209 W/m² incident on an inclined solar PV collector for daily optimum tilt angle. While MA Iqbal model performs best for the monthly solar radiations on the inclined surface.

A comparison of the percentage enhancement of H_T on a tilted surface between monthly optimum and latitude tilt for Lahore and Khuzdar is presented in Fig. 7. A minimum of 5% to 10 % enhancement in the collection

of H_T is seen for Lahore while a 6% to 11% increase in the value of H_T is observed for Khuzdar. Using this information monthly optimum tilt angles for selected stations were computed against each solar diffuse model.



Fig. 7. Percentage Increase in H_T for Monthly Optimum Tilt as Compared to The Latitude Tilt



Fig. 8. Comparison of Monthly Optimum Tilt Angle for Isotropic and Anisotropic Sky Diffuse Models for (a) Lahore and (b) Khuzdar Stations

A comparison was also made between monthly optimum tilt angle for the selected stations against isotropic and anisotropic models. The results for Lahore which has the minimum K_T value of 0.49 and Khuzdar with maximum K_T of 0.68 are shown in Fig. 8.

The optimum tilt angle is dependent upon site latitude and declination angle. It can be seen that for any specific month the optimum tilt angle is different for every station and thus, varies with the site latitude. As the declination angle is increasing from December solastic to June solastic the optimum tilt angle is decreasing. From June to onwards the sun's declination angle starts increasing and corresponding to that the value of optimum tilt angle increases. During the month of the December the monthly averaged daily optimum tilt angle is 55.6° that falls to 0° in June/July during which the declination angle is from $+23.17^{\circ}$ to $+21.37^{\circ}$

Monthly adjustment of solar PV to an optimum tilt as compared to annual tilt adjustment, allows the improved collection of H_T on the tilted surface. All the models are compared to observe the enhancement of total radiations impinging the tilted surface for selected sites.

5. Conclusion

A comparison was made between different isotropic and anisotropic sky models. The Gueymard model gives maximum mean annual solar radiation incident on an inclined solar PV collector for daily optimum tilt angle. The variations in optimum tilt angle for whole year were observed to be non-uniform. It nearly remains zero for Spring and Summer seasons, then it shows an increasing trend to 75° for Autumn and Winter seasons. The Gueymard model gives maximum mean annual solar radiation incident on an inclined solar PV collector for

daily optimum tilt angle. While M.A Iqbal model performs best for the monthly solar radiations on inclined surface due to modified value of K_T . Almost for all locations the sun follows longer path in summer season, and daily optimum tilt angle in these months is nearly 0°, while in winter solastic the daily optimum tilt angles are maximum as the sun tracks a shorter path. This maximum daily optimum tilt angle is found to be nearly 75° for Lahore and it occurs in December. The yearly fixed optimum tilt angle for solar PV panels in Lahore and Khuzdar is nearly equal to the latitude of the site. More than 11% and 13% increase in monthly mean daily irradiance on the tilted surface is observed compared to irradiance on a horizontal surface for Lahore and Khuzdar stations respectively. The ratio of total mean annual radiations falling on the tilted surface is nearly 1.2 and 1.3 times of H_g for Lahore and Khuzdar respectively. The amount of solar irradiance on a tilted surface shows a good agreement with the K_T . A site with a greater sky clearness index will experience a higher amount of solar irradiance. Almost a 6-11% increase in the H_T is observed for monthly optimum tilt as compared to the latitude for both Lahore and Khuzdar.

7. References

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D-04. Car-Integrated Photovoltaics

Impact of Photovoltaics-powered Vehicles

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Abstract

Development of high-efficiency solar cell modules and new application fields such as PV (Photovoltaics)powered vehicles are significant for the further development of PV and the creation of new clean energy infrastructure based on PV. In this paper, analytical results for impact of high-efficiency solar cell modules on increasing driving distance, reducing CO₂ emission and saving charging cost of electric vehicles by PV-powered vehicles are presented. Because the Si tandem solar cells are expected to have significant potential for PVpowered vehicle applications, potentials of high-efficiency of Si tandem solar cells and driving distance of vehicles installed with Si tandem solar cells are also analyzed. The III-V/Si 3-junction solar cell modules with more than 35% have potential of driving distance of more than 30 km/day average and more than 50 km/day on a clear day.

Keywords: vehicle applications, high-efficiency, driving distance, CO_2 emission reduction, tandem solar cells and modules,

1. Introduction

Development of the PV(photovoltaics)-powered vehicleis (Yamaguchi et al., 2017a, NEDO, 2018, Rodriguez et al., 2019, Yamaguchi et al., 2020, Yamaguchi et al., 2021) is desirable and very imortant in order to creat new clean energy society. In order to enhance recognizing the PV-powered electric vehicles (PV-EV) as major clean vehicles and to create clean energy society based on PV, clarifying values of PV-EV and development of high-efficiency, low-cost, light-weight, 3-demensional curved and colorful solar cell modules and other technologies are necessary. This paper presents the importance of developing high-efficiency solar cell modules, especially Si tandem solar cells for PV-powered vehicles. In this paper, analytical results for effectiveness of high-efficiency Si tandem solar cell modules from point-views of driving distance, reduction in CO_2 emission and saving EV charging cost are shown.

2. Analysis for high-efficiency Impact on driving distance of PV-powered vehicles

Solar cell module efficiency impact on driving distance of PV-powered vehicles (PV-EV) was calculated. In the calculations, the charging system efficiency of 73.9% (Masuda et al. 2017) composing of cell temperature correction, maximum power point tracking, DC/DC conversion, and DC charging were assumed. Figure 1 shows calculated driving distance of PV-powered vehicles in the case of electric mileage of 9.35 km/kWh and solar irradiance 4kWh/m²/day as a function of PV module nominal power in comparison with practical data for Toyota Prius 2019 (Yamaguchi et al., 2021), Toyota Prius 2017 (Yamaguchi et al., 2021), and Sono Motor Sion (Sono Motors). The Toyota Prius 2019 (demonstration car) (Yamaguchi et al., 2021) installed with about 30.9% efficiency module and output power of 860W has shown 29.9km/day driving distance at solar irradiance of 4.1kWh/m²/day. On the other hands, the Sono Motor Sion (Sono Motors) installed 20-22% efficiency module has shown 15.3km/day average (solar irradiance of 3.84kW/m²/day). It is clear that the higher-efficiency solar cell modules are promising for realizing the longer driving distance as shown in Fig. 1.

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Fig. 1: Calculated driving distance of PV-powered vehicles in the case of electric mileage of 9.35 km/kWh and solar irradiance 4kWh/m²/day as a function of PV module nominal power in comparison with practical data for Toyota Prius 2019, Toyota Prius 2017 and Sono Motor Sion. Blue colour plots show clear day data and red colour plots shows average driving distance.

3. Analysis for high-efficiency impact on CO₂ emission reduction by PV-EV

Effects of introduction of high-efficiency solar cell modules into EVs upon reduction in CO_2 emission were analysed. Average CO_2 emission intensity CI_{EV} for EVs is reported to be 462 g- CO_2 e/kWh (Ministry of the Environment). EV usage CO_2 emission CE_{EV} is expressed by

 $CE_{EV}[g-CO_2 e/km] = CI_{EV}[g-CO_2 e/Wh]EC_{EV}[Wh/km]) = CI_{EV}[g-CO_2 e/Wh]/EM[km/Wh]), (eq. 1)$

where EC_{EV} is the EV energy consumption and EM is the electric mileage. On the other hands, CO_2 emission $CE_{PV-production}$ for PV-production is thought to be given by

 $CE_{PV-production}[g-CO_2 e/km] = P_{pv}[W]CI_{PV}[g-CO_2 e/W]/(DD [km/day]\tau_{PV} [years]), (eq. 2)$

where P_{pv} is the module output power, CI_{PV} is the carbon intensity per unit W, DD is the driving distance, and τ_{PV} is the lifetime for PV modules. In this study, 1,008 g-CO₂ e/W was assumed as CI_{PV} according to the reference (Kanz et al., 2020) and 15 years were assumed as τ_{PV} because of PV-powered vehicle applications. The PV-EV usage CO₂ emission CE_{PV-V} is expressed by

 $CE_{PV-EV}[g-CO_2 \ e/km] = CE_{EV}[g-CO_2 \ e/km] + CE_{PV-production} \ [g-CO_2 \ e/km]. \ (eq. \ 3)$

Tendency for cumulative frequency CF of passenger cars in Japan (Hara et al., 2016) as a function of daily mileage was approximated by the following equation:

 $CF = 0.9\{1-EXP(-DD[km/day]/20)\}/0.1\{1-EXP(-DD[km/day]/200\}.$ (eq. 4)

As shown in Section 2, driving distance DD was estimated by using the following equation:

 $DD[km/day] = SI[kWh/m^2/day]PR*\eta[\%]*0.01A [m^2]EM[km/kWh], (eq. 5)$

where SI is the solar irradiance, PR the performance ratio of PV system and 0.739 [6] was used as the PR in this case, A is the area of solar cell module and 3 m² was used as A this time, and EM is the electric mileage. In the calculation, sharing ration of EV mode and PV mode for PV-EV was estimated by driving distance DD and eqs 1-5.



Fig. 2: Calculated results for CO₂ emission of PV-powered electric vehicles (PV-EV) installed with solar cell modules with different efficiencies as a function of electric mileage in comparison with those of electric vehicles (EV) and PV production.

Figure 2 shows calculated results for CO_2 emission of PV-EV installed with solar cell modules with different efficiencies as a function of electric mileage in comparison with those of EV and PV production. It is clear in Figure 2 that the PV-EV installed with the higher efficiency solar cell modules has great potential of reduction in CO_2 emission. 55% - 73% CO2 reduction will be realized by using the PV-powered vehicles with electric mileage of 10km/kWh.

4. Analysis for high-efficiency impact on EV charging cost saving by PV-EV

Electricity cost saving for EV charging by usage of PV was analysed in this study. EV energy consumption EC is given by

EC [kWh/year] = DD [km/year]/EM [km/kWh]. (eq. 6)

Charging electricity cost CC of EV charging is given by

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CC [$/year] = EC [kWh/year]* EP [$/kWh], (eq. 7)
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where EP is the household electricity and is 0.2/kWh in Japan in 2020 (Global Petrol Prices). PV-EV cost saving ΔCS_{PV-EV} was calculated by using the following equation

 ΔCS_{PV-EV} [\$/year] = - ΔE_{grid} [kWh/year]*EP [\$/kWh]. (eq. 8)

In the similar way with analytical procedure described in Section 3, effectiveness of high-efficiency solar cell modules for cost saving of EV charging was analysed. By using eq. 4 for tendency for cumulative frequency CF of passenger cars in Japan as a function of daily mileage, charging possibility of PV-powered vehicles was calculated. Cost saving for charging of EV was calculated by considering reduction in charging frequency due to usage of PV and using eq. 8.

Figure 3 shows calculated results for charging electricity cost of EV and PV-EV as a function of electric millage by assuming 30 km/day as average daily driving distance. The results show effectiveness of high-efficiency solar cell modules for charging electricity cost saving of electric vehicles. For example, electricity cost saving is \$254.1/year for 40% module and \$149.1/year for 20% module in the case of electric mileage of 4 km/kWh, \$167.2/year for 40% module and \$117.8/year for 20% module in the case of electric mileage of 10 km/kWh.



Fig. 3: Calculated results for charging electricity cost of EV and PV-EV as a function of electric mileage by assuming 30 km/day as average daily driving distance.

5. Analysis for driving distance of vehicles powered by Si tandem solar cells

As described above, the higher-efficiency solar cell modules have great potential for the longer driving distance, reduction in CO_2 emission and saving charging cost for electric vehicles. However, cost reduction of solar cell modules is also very important for attractive PV-powered vehicles. The Si-based tandem cells (Yamaguchi et al., 2018a, Essig et al., 2017) that combine Si with other materials such as III-V compound, II-VI compound, perovskite chalcopyrite, and so forth are desirable for realizing super high-efficiency and low cost. The Si tandem solar cells have been receiving considerable attention because of its potentials.



Fig. 4: Calculated 1-sun efficiency of III-V/Si triple-junction including our results III-V/Si and dual-junction tandem solar cells and perovskite/Si dual-junction tandem solar cells as a function of average external radiative efficiency (ERE) and resistance loss $_{s} + 1/r_{ss}$. White rectangular shows InGaP/GaAs/InGaAs triple-junction tandem solar cells.

Previously, we have analyzed the efficiency potential of various solar cells by using our analytical procedure (Yamaguchi et al., 2017b, 2018c, 2018c). In the analysis for efficiency potential of Si tandem solar cells, the

similar method and parameters reported in our previous papers (Yamaguchi et al., 2017b, 2018c, 2018c) were used. Figute 4 shows calculated 1-sun efficiency of III-V/Si triple-junction including our results and III-V/Si dual-junction tandem solar cells and perovskite/Si dual-junction tandem solar cells as a function of average external radiative efficiency (ERE) and resistance loss $r_s + 1/r_{ss}$. White rectangular and circle plots show InGaP/GaAs/InGaAs triple-junction and InGaP/GaAs dual-junction tandem solar cells.

Previously, we have achieved 28.2% efficiency (0.95 -cm² da) (Yamaguchi et al., 2018a, 2016a, 2016b) in 2016, and Sharp demonstrated 33% (Takamoto et al., 2017) (3.604-cm² ap) in 2017, with mechanically stacked InGaP/GaAs/Si 3-junction solar cells. At present, the III-V/Si 3-junction and 2-junction tandem solar cells have shown higher efficiency with 35.9% (Essig et al., 2017) (1.002-cm² da) and 32.8% (Essig et al., 2017) (1.003-cm² da) compared to perovskite/Si 2-junction tandem solar cells with efficiencies of 29.15% (1.030-cm² da) (Al-Ashouri et al., 2020) and CdZnTe/Si 2-junction tandem solar cell with an efficiency of 16.8% (0.126-cm² mesa area) (Cormody et al., 2010). Such an efficiency difference is thought to be a difference in material quality. For example, the external radiative efficiency values (ERE) are 1-2.2% for III-V/Si tandem cells, 0.1-0.17 % for perovskite/Si tandem cells, 0.0016 % for CdZnTe/Si tandem cells. Therefore, a material quality is critical for further improvements in the performance of Si tandem solar cells. Although efficiency (35.9%) (Essig et al., 2017) of 4-terminal mechanical stacked InGaP/GaAs/Si 3-junction tandem solar cells is close to that of InGaP/GaAs/InGaAs 3-junction cells (37.9% for 1.047-cm² ap) (Sasaki et al., 2013), resistance loss is higher as shown in Figure 4. Resistance loss for the perovskite/Si tandem cells and CdZnTe/Si tandem cells are much higher compared to the III-V/Si tandem solar cells as shown in Figure 4. The 3-junction and 2-junction Si tandem solar cells have an efficiency potential of 42% and 36%, respectively.

Figure 5 shows calculated results for driving distance of vehicles powered by perovskite/Si 2-junction, III-V/Si 2-junction and III-V/Si 3-junction tandem solar cells and III-V 3-junction tandem solar cells and module as a function of module efficiency and temperature coefficient (TC) in comparison with estimated values of vehicles powered by perovskite/Si 2-junction, II-V/Si 2-junction and III-V/Si 3-junction tandem solar cells and III-V 3-junction tandem solar cells and module and actual driving distance calibrated of the Prius 2019 (Yamaguchi et al., 2021) powered by III-V 3-junction solar cell module and the Sono Motors Sion (Sono Motors) powered by back-contact Si solar cell module. The III-V/Si 3-junction solar cell modules have potential of driving distance of 30 km/day average and more than 50 km/day on a clear day.



Cell and module efficiency (%)

Fig. 5: Calculated results for driving distance of vehicles powered by perovskite/Si 2-junction, III-V/Si 2-junction and III-V/Si 3-junction tandem solar cells and module as a function of cell and module efficiency and temperature coefficient (TC) in comparison with estimated values of vehicles powered by perovskite/Si 2-junction, III-V/Si 2-junction and III-V/Si 3-junction tandem solar cells and module and actual driving distance calibrated of the Prius 2019 [1] powered by 3-junction solar cell module

6. Summary

The development of PV-powered vehicle applications is desirable and very important for reducing CO₂ emission of vehicles and creation of mobility society.

This paper presented importance of developing PV-powered vehicles from points-views of re-duction in CO2 emission, charging cost reduction for electric vehicles and reducing storage capacity of PV-powered electric vehicles.

This paper has shown that reduction of 55% - 73% CO2 emission will be realized by using the PV-powered vehicles with electric mileage of 10km/kWh and the higher-efficiency solar cell modules have possibility of great contribution to CO2 emission reduction in the PV-powered vehicles.

The results also have shown the effectiveness of high-efficiency solar cell modules for charging electricity cost saving of electric vehicles. For example, electricity cost saving is \$254.1/year for 40% module and \$149.1/year for 20% module in the case of electric mileage of 4 km/kWh, \$167.2/year for 40% module and \$117.8/year for 20% module in the case of electric mileage of 10 km/kWh.

In this paper, analytical results for effectiveness of high-efficiency solar cell modules from point-views of driving distance, reduction in CO2 emission and saving EV charging cost were shown. The Si tandem solar cells are expected to have significant potential for PV-powered vehicle applications because of high efficiency with efficiencies of more than 42% under 1-sun AM1.5 G, lightweight and low-cost potential. It is summarized that the III-V/Si 3-junction solar cell modules with module efficiency of more than 35% have potential of driving distance of more than 30 km/day average and more than 50 km/day on a clear day.

7. Acknowledgements

The authors thank members of the NEDO, METI, and Toyota Tech. Inst., Sharp Co., Toyota Motor Co., Nissan Motor Co., and to Mr. M. Yamazaki, Dr. H. Yamada, Mr. M. Ishimura, Mr. K. Fukushima, Mr. M. Iwata, Mr. T. Sato, and Ms. M. Hasegawa, NEDO, Dr. T. Takamoto, Sharp, Prof. K. Nishioka and Prof. Y. Ota, Univ. Miyazaki, Mr. A. Satou, Mr. K. Okumura, Mr. T. Nakado, and Mr. K. Yamada, Toyota Motor, Dr. Y. Zushi, and Mr. T. Tanimoto, Nissan Motor, Dr. K. Nakamura, Mr. R. Ozaki, Dr. N. Kojima, and Prof. Y. Ohshita, Toyota Tech. Inst., Prof. N. Yamada and Dr. D. Sato, Nagaoka Univ. Tech., Prof. T. Hirota, Waseda Univ., Dr. K. Komoto, Mizuho, Inf. Res. Inst., Dr. M. Tanaka, PVTEC, and members of the NEDO's PV-powered Vehicle Strategy Committee for their helpful discussion and providing fruitful information.

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D-05. Infrastructure Photovoltaics

Influence of terrain on single-axis PV plants

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Abstract

This paper presents a systematic study of the influence on the radiation capture of the azimuth angle of horizontal one-axis trackers as well as the inclination and azimuth of the terrain where they are built. The results prove that, to optimize the radiation capture and, consequently, the energy production, for South facing terrains, the tracker rotation axis must be also oriented to the south for any terrain inclination. Additionally, when both the terrain and the rotation axis of the trackers are oriented to the South, the radiation capture increases with the inclination of the terrain until a maximum. However, for not south facing terrains, the rotation axis azimuth of solar trackers should be deviated from the South in the same direction as the terrain azimuth. Finally, in this case of not south facing terrains, the loss of radiation increases with the azimuth of the terrain.

Keywords: Photovoltaics, Horizontal one-axis Tracking, Backtracking, Inclination of the Terrain, Azimuth of the Terrain.

1. Introduction

The environmental challenges that society is currently facing worldwide are fostering the development of renewable energies since they contribute to a more efficient and sustainable energy system (United Nations, 2019). In this context, applications based on the use of solar energy, in general, and photovoltaic (PV) energy, in particular, have an essential role to play due to the fact that the cost of energy generation associated with them has decreased significantly in recent decades thanks to technological development and research (Renewable Energy Agency, 2020; Ribó-Pérez et al., 2019).

However, the strong temporal dependence of solar energy or the negative effects that shadows produce on PV collectors make it necessary to promote new technological developments that mitigate the impact of these phenomena on energy production (Gómez-Uceda et al., 2020).

In this sense, solar tracking is presented as a solution to the strong temporal dependence of solar radiation (Hua et al., 2019). In this way, solar collectors follow the sun's path throughout the day and the year, thereby increasing solar capture and, therefore, energy production (Bahrami et al., 2016). For that reasons, multiple research on tracking is being developed to enhance the technology and its efficiency while reducing its cost (Eldin et al., 2016).

For this solar tracking, the classical tracking strategy proposes the astronomical model based on the relative Earth-Sun motion. However, several studies have shown that this is not the optimal strategy for cloudy days. The reason for this is that astronomical tracking aims to optimize the direct component of solar radiation; however, on cloudy days this component loses relevance compared to the diffuse and reflected components (Duffie & Beckman, 2013). Therefore, it is necessary to continue research on solar tracking strategies that consider the global behavior of solar radiation and not only its direct component.

On the other hand, inter shading between PV collectors reduce the radiation capture and increases the temperature of the shading PV cells that work as resistive loads and negatively influences to the functioning of the plant (Belhachat & Larbes, 2015; Satpathy & Sharma, 2019; Seyedmahmoudian et al., 2016). Multiple

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research is being developed to study the reduction in PV production due to shading (Saint-Drenan & Barbier, 2019; Satpathy & Sharma, 2019). Backtracking is a technological solution to avoid inter-shading between collectors in PV plants with tracking (Gómez-Uceda et al., 2021; Panico et al., 1992). It consists of deviating the collectors with respect to the maximum capture orientation to a new position where there is no intershading, thus mitigating the negative effects of the latter (Figure 1).

However, although both problems have been widely studied, most of the previous research has studied PV facilities located on horizontal terrains. In this context, this work presents a systematic study of the influence of the terrain characteristics (inclination and elevation) on the radiation capture of horizontal one-axis PV plants.



Fig.1. Fundamentals of Backtracking. Part (a) shows a situation in which one tracker shadows the next. This shadow can be avoided by decreasing the tilt of the trackers (part B)

2. Materials and Methods

For that purpose, the solar radiation reaching the collectors of a PV plant with horizontal one-axis trackers is analyzed for different terrain and collector configuration. The Hay-Davis Method (Hay, 1993) is used to estimate the solar irradiance. This method considers that the solar irradiance, I, is composed of three components: direct, diffuse, and reflected. Thus, in vectorial notation, it is given by eq. (1), where I_0 is the horizontal extraterrestrial solar irradiance, I_B and I_D are, respectively, the direct and diffuse irradiance on a horizontal surface, ρ is the albedo of that horizontal surface, and, \vec{k} , \vec{n} and, \vec{s} , are, respectively, the vertical unitary vector, the normal vector to the collectors, and the solar vector, defined all of them in the terrestrial reference system.

$$I = \frac{\vec{s} \cdot \vec{n}}{\vec{s} \cdot \vec{k}} I_B + \left[\left(\frac{\vec{s} \cdot \vec{n}}{\vec{s} \cdot \vec{k}} \right) \frac{I_B}{I_{OH}} + \left(1 - \frac{I_B}{I_{OH}} \right) \frac{1 + \vec{k} \cdot \vec{n}}{2} \right] I_D + \rho \frac{1 - \vec{k} \cdot \vec{n}}{2} (I_B + I_D)$$
(eq. 1)

Specifically, the solar vector, \vec{s} , is a unitary vector pointing the Sun and given by eq. (2) where δ is the solar declination, φ is the latitude of the location considered and $\Omega t = (2\pi/24 \ rad/h)t$ is the hour angle.

 $\vec{s} = \sin \Omega t \cos \delta \vec{i} + (\cos \Omega t \cos \delta \sin \varphi - \sin \delta \cos \varphi)\vec{j} +$

+ (cos Ω t cos δ cos
$$\varphi$$
 + sin δ sin φ)k

From eq. (1) considering *I* as function depending of \vec{n} it is possible to optimize the solar irradiance *I* by applying the Lagrange multiplier method. In this work, this methodology is applied to PV plants with horizontal one-axis trackers whose rotation axis has an azimuth angle γ . Furthermore, the ground on which the PV plant is built is considered not to be horizontal but to have an inclination and azimuth β and χ , respectively. Thus, the normal vector to the ground, \vec{e} , is given by eq. (3).

$$\vec{e} = \frac{\cos\beta \cdot \sin\gamma}{\sqrt{\sin^2\beta + \cos^2\beta \cos^2(\gamma - \chi)}} \vec{i} + \frac{\cos\beta \cdot \cos\gamma}{\sqrt{\sin^2\beta + \cos^2\beta \cos^2(\gamma - \chi)}} \vec{j} - \frac{\sin\beta \cdot \cos(\gamma - \chi)}{\sqrt{\sin^2\beta + \cos^2\beta \cos^2(\gamma - \chi)}} \vec{k}$$
(eq. 3)

(eq. 2)



Fig.2. Geometry analysis of inter-shading between collectors.

On the other hand, according to Fig. 2, inter-shading between the PV collector will take place when the module of the vector \vec{a} is smaller than the width of the panels, *h*. As a solution, in this work, backtracking is proposed in order to avoid shading between collectors. Specifically, when inter-shading between collectors occurs, the collectors are deviated from its original position the minimum angle that avoids shading.

3. Results

The methodology described has been applied to a horizontal one-axis PV plant situated at a location of 37.75492° N latitude and -5.04548° longitude. To study the influence of the terrain on the solar irradiance capture when the trackers move according to the tracking/backtracking strategy proposed, the inclination of the terrain β has been varied from 0° to 45° (1° steps) and its azimuth χ has been varied form -60° to 60 ° (5° steps). Furthermore, the azimuth of the rotation axis of the trackers γ has also been varied form -20° to 20 ° (2° steps). The width of the collectors and the distance between the collector lines have remained constant, being h = 3m and d = 6m, respectively.

It has been found that, whatever the inclination of the terrain, the maximum solar irradiance values are registered when the azimuth of the terrain is zero. Furthermore, for all terrain inclinations, when the terrain is oriented towards the south, the orientation angle of the solar trackers that optimizes solar capture must also be zero. Therefore, the most favorable situation will be when both the terrain and the axis of rotation of the trackers are oriented towards the south.

However, it has been found that when the terrain does not face south, the optimum angle for the axis of rotation of the solar trackers must also deviate from the south in the same direction as the terrain, and that this behavior is accentuated for terrain with high inclinations. As an example, Fig.3 shows the results for the case of a terrain with an inclination angle (β) of 15°. Specifically, it represents the radiation vs. the azimuth of the rotation axis of the trackers when the terrain is oriented towards the South direction, that is, $\chi = 0$, (Fig. 2a) and when $\chi = 30^{\circ}$ (Fig. 2b). It can be seen that, in the first case ($\chi = 0^{\circ}$), the maximum radiation is captured when the tracker rotation axis is also orientated towards the South ($\gamma = 0^{\circ}$) whereas, in the second case ($\chi = 30^{\circ}$), it must be deviated 6°. Fig. 4 shows the most favorable orientation of the rotation axis of the trackers for different azimuth of the terrain when its inclination is 15°.



Fig.3. Dependence of solar radiation on the tracker axis azimuth for: a) $\beta = 15^{\circ}$ and $\chi = 0^{\circ}$ and b) $\beta = 15^{\circ}$ and $\chi = 30^{\circ}$



Fig.4. Optimal orientation of the rotation axis of the trackers for terrain with 15° of inclination and different azimuth χ

On the other hand, Fig. 5a shows that, when the terrain and the tracker rotation axis are oriented to the South, the radiation increases with the inclination of the terrain until a maximum value which, in the case of the location considered (37.75492° N latitude and -5.04548° longitude), occurs for $\beta = 21°$. Finally, for a fixed terrain inclination of $\beta = 20°$, Fig. 5b shows the influence of the azimuth on the radiation capture, on terms of the losses respect to the maximum irradiance that, as mentioned before, occurs when $\chi = 0°$ and $\gamma = 0°$. It can be seen that these losses increase with the azimuth of the terrain.



Fig.5. Influence on the maximum radiation capture of: a) the inclination of the terrain when $\chi = 0^{\circ}$ and $\gamma = 0^{\circ}$ and b) the azimuth of the terrain when $\beta = 20^{\circ}$ and $\gamma = 0^{\circ}$

4. Conclusions

This work presents a systematic study of the influence of the inclination and the azimuth of the terrain on the maximum radiation capture by the collectors of a horizontal one-axis PV plants located on that terrain whose trackers moves according to a backtracking strategy that tries to avoid inter-shading between PV collectors. Furthermore, the azimuth of the tracker rotation axis has also be considered for this study. The results show that, for any inclination of the terrain, the maximum radiation capture will take place when the terrain and the tracker rotation axis are oriented to the South. For other terrain azimuth, the higher the azimuth, the higher the losses will be. Additionally, it has been proved that the angle orientation of the rotation axis of the trackers must be deviated in the same direction as the terrain in order to maximize the solar capture. Thus, this work contributes to the characterization of one-axis PV plants and the optimization of its radiation capture, and, consequently, of its energy production.

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Solar energy for self-sufficient electric aircraft operations at Bardufoss flight school

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Abstract

Electric transport powered by renewable energy is key to reduce the climate impact of the transport sector. Significant resources are put in to developing larger electric and hybrid-electric passenger aircraft, but the first electric aircraft will be small and short-range. Flight schools are well set to be early adopters of electric aircraft. This paper presents the experiences from the first year of operation of electric aircraft at University of Tromsø School of Aviation (UTSA) in Bardufoss in Northern Norway. A façade-mounted 100 m² PV system at the airport provides power to the aircraft. First year measurements show an energy yield of 618 kWh/kWp. If the aircraft were used in regular pilot training (which they are not due to their status as "Experimental) the system could supply energy for around 700 flight hours with the electric aircraft, giving an annual self-sufficiency of the operations of 0.83.

Keywords: self-sufficiency, solar airports, electric aircraft

1. Introduction

The transport sector is one of the major contributors to greenhouse gas emissions globally and in Norway. In Norway, the transport sector accounts for 24% of the energy demand, but 33% of the greenhouse gas emissions (OED, 2021). Electric transport powered by renewable energy is a key to reduce the sector's climate impact. Other technologies, such as hydrogen fuel cells and sustainable biofuels, are also part of the solution. Electric vehicles for road, rail and sea transport are becoming more and more widespread, but aviation is one of the most difficult sectors to electrify due to the weight restrictions, high safety requirements and because it is impossible to charge during operation. There are now over 200 research and development projects around the world involving electric aircraft (Thomson, 2020). Although significant resources are aimed at developing larger electric and hybrid-electric passenger aircraft, the first certified electric planes will doubtless be small, short range, and operate low-passenger routes.

Flight schools are well suited to be early adopters for electric aircraft. Most training flights are relatively short with only one student and one instructor. This is proven by the interest in the he all-electric eFlyer, a 2 or 4 seat training aircraft which is currently in development by Bye Aerospace (Bye Aerospace, 2021). The aircraft has already been pre-ordered by among others OSM Flight Academy, Reykjavik Flight Academy in Iceland, and KLM Flight Academy in the Netherlands (Future Flight, 2021). Since electric aircraft are less costly to operate and require less maintenance, there are also economic arguments for switching to electric training aircraft.

A widespread adoption of electric aircraft will require significant amounts of power for charging. In addition, aviation includes more than the aircraft: A fully electric aviation sector will also contain vehicles and services on the airport side, such as cars, buses, fire trucks, snow removal, catering, cleaning, and de-icing, and possibly also charging infrastructure for transport to and from the airport, such as buses, taxis and personal vehicles (Energi Norge, 2020). In addition, there is the power requirements of the operation of the airport buildings.

Airports are often well suited for solar energy installations, with large available building areas and little shading from the surroundings (Kandt and Romero, 2014). Solar energy is therefore set to contribute to low emission aviation. However, strict safety considerations for airport installations are important to ensure that the installations do not disturb or interfere with aircraft operations. In particular this is related to avoiding glint and glare, but there may also be other safety issues concerning the distance from the airport or fire hazard (Kandt and Romero, 2014). The Federal Aviation Administration (FAA) in the United States has recently issued a policy for safe solar installations at airports (FAA, 2021).

This paper presents the experiences from the introduction of electric aircraft powered by local solar energy at University of Tromsø School of Aviation (UTSA) in Northern Norway. UTSA is a part of UiT The Arctic University of Norway operates out of Bardufoss airport in Northern Norway. The flight school admits 24 students yearly to the

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bachelor's programme in Aviation, where the students also gain a Commercial Pilot License (CPL).

Bardufoss is located north of the Arctic Circle and has polar night between 30 November and 12 January, meaning that the sun does not rise above the horizon. Conversely, the period with midnight sun, when the sun never sets below the horizon, ranges from 23 May and 1 July. The available solar resource is therefore very unevenly distributed over the year. The location in Northern Norway also means that the weather conditions can be harsh, especially during winter, and the topography challenging. This puts special demands on both pilots and equipment.

2. Method

2.1 Electric aircraft

In 2018, UiT and UTSA bought two small electric aircraft of the type Pipistrel Alpha Electro (Fig. 1, left) as part of a research project on electric aviation. The two-seater aircraft can carry a total load (pilot and passenger) of 180 kg, with an endurance of around 1 hour plus safety margin. The aircraft are powered by a 60 kW electric engine and have a battery capacity of 21 kWh (Pipistrel, 2018). According to Pipistrel, the batteries are designed to be easily and quickly replaced or charged in less than an hour. In practice, the batteries are charged using a portable 20 kW charger.

Due to issues with the battery, only one of the aircraft (LN-EON) has so far been airborne. The aircraft has logged around 45 flight hours around Bardufoss Airport and gathered data for research. Among the objectives are to study the energy performance of the aircraft in at different conditions and types of operation, battery life and degradation, as well as requirements on airport infrastructure for electric aviation. An additional focus is operations in Arctic and northern conditions, including difficult topography and harsh weather conditions.



Fig. 1: One of the two Pipistrel Alpha Electro aircraft at Bardufoss Airport. Photo: Tomas Rolland, UiT.

As in all aircraft operations, safety is an overarching focus. The aircraft were originally intended to be used in regular training at the flight school, but this has not been possible since the Alpha Electro is still classified as "Experimental" and therefore not certified for regular operation. The planes are therefore only flown by specially trained flight instructors at UTSA, using strict safety protocols. Last year, however, Pipistrel launched the Velis Electro, which is an EASA (European Union Aviation Safety Agency) certified version of the same aircraft frame (Pipistrel, 2021). Other electric trainers are also set to be certified. Bye Aerospace, for example, has projected to have certification of its eFlyer 2 by the end of 2022, or possibly even earlier (Future Flight, 2021).

The calculations in this study are made for an imagined scenario where the aircraft are used in ordinary pilot training. In this scenario, it is estimated that they would fly two training rounds per day each, giving a total of four daily flight hours. Since the Alpha Electro lacks de-icing capabilities, the aircraft are only operated in conditions without risk of icing, and it is estimated that this period lasts from April to October. In total, this means 846 flight hours per year.

2.2 Solar energy system

A photovoltaic (PV) solar energy system (Fig. 2) was installed at the airport to provide local renewable power to the electric aircraft operations. The 100 m² PV system was installed on the south-facing wall of UTSA's hangar building,

directly facing the air strip. The system consists of 58 modules with a total installed power on 19.2 kWp. The modules are 330 Wp monocrystalline half-cell modules from JA Solar (JAM60S10-330-PR-SF). The system is connected to the grid via a 15 kW Ginlong Solis inverter (SOL-15.0-3PH-4G-DC).



Fig. 2. The 100 m² photovoltaic system at Bardufoss Airport. Photo: Clara Good.

When installing the system, it was discussed whether modules should also be placed on the roof of the hangar. An installation on both roof and façade would have made possible a larger installation, and the solar energy would have been more evenly distribution of energy over the day and year. The roof-mounted option was eventually not chosen for two main reasons. Firstly, there were uncertainties about the durability of the construction, and whether it would be able to hold the extra weight in addition to the already high rated snow load. The second reason was uncertainty regarding reflections from modules, and how this might affect the air traffic. As mentioned in the introduction, there are now guidelines and policies for how to safely install PV systems at airports (FAA, 2021, Kandt and Romero, 2014), and it might be possible to extend the installations to the roof a proper analysis of the consequences.

Vertical installations, such as on building facades, is generally a good option in northern regions, since the sun angle is relatively low. The maximum sun angle in Bardufoss is around 45° during summer, and it is lower in spring, winter and autumn. Another benefit of vertical installations is that it reduces the problem of snow accumulating on the modules, which may lead to reduced energy yield, and in extreme cases also structural damage to the modules.

2.3 Solar self-sufficiency

One of the objectives of the PV installation at the airport was for the operation of the electric aircraft to be selfsufficient on local renewable energy. That is, that the solar energy generated by the PV system would be enough to power all operation of the electric aircraft throughout the year.

Solar self-sufficiency can be defined as the self-consumed part of the solar energy yield relative to the total load (Luthander et al., 2015). It follows that even though two systems may have the same self-consumed energy in absolute terms (kWh), their relative self-sufficiency can be different if the total load is different. Using the terminology from Luthander et al. (2015), the solar fraction can be described by

$$\varphi_{ss} = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} L(t)dt},$$
 (eq. 1)

where M(t) is the instantaneously overlapping part of the PV generation, P(t), and the load, L(t), defined by

$$M(t) = \min \{L(t), P(t)\}.$$
 (eq. 2)

In addition to the load and generation profiles, the self-sufficiency depends, among other things, on the time resolution t and the period of integration. In the analysis presented here, the time resolution is one month, and the period of analysis is one year. In further analyses of the data, the calculations will be made for a smaller time resolution, e.g. one hour, and a battery storage may also be introduced.

In addition to the monthly and yearly self-sufficiency, the number of generated flight hours are calculated. In this case, calculations are performed also for the months when there are no operations due to risk of icing.

3. Results

3.1 Electric aircraft performance

The aircraft at UTSA are operated with a safety margin of 20% battery reserve, that is, the required state of charge (SOC) at landing. The aircraft has so far been flown in training patterns with varying power requirements. Based on the experiences of the pilots so far, a very rough estimate is that the endurance during a "normal" flight from A to B in good weather conditions is 1 hour plus safety margin, giving an estimated energy performance of 16.8 kWh per flight hour, based on a battery capacity of 21 kWh.

In the scenario where the aircraft would be incorporated into normal operation at the flight school, with four flight hours per day, the energy demand is 67.2 kWh per day. Assuming operation from April to October, the total annual energy demand of the aircraft would be 14381 kWh, or on average 2054 kWh per month.

Assuming that the four flights would be distributed throughout the day, the energy demand would be distributed over four charging sessions. A very simplified distribution is presented in Fig. 3. In reality, it may be that especially the two later charging sessions of the day would be done at lower power, in order to preserve battery health. It could also be that the charging sessions would be planned based on the available solar energy, or the charging level of an external battery storage.



Fig. 3. A simplified version of the hourly energy demand for charging the electric aircraft.

Analysis of the gathered flight data will be used to determine a more detailed understanding of the energy performance in different types of operation. This is a topic for current and future research.

3.2 Solar energy generation

The PV system at Bardufoss has been operational since November 2019. The total measured solar energy yield during 2020 was 11872 kWh or 618 kWh/kWp, which was very close to estimations. The monthly distribution in 2020 is shown in Fig. 4, which also includes measurements up until September 2021. If the yield in the remaining three months of 2021 is the similar to that in 2020, the total energy yield in 2021 will be 11812 kWh, or 615 kWh/kWp.

The location above the Arctic Circle is reflected in the data in Fig. 4. The energy yield during the polar night in November, December and January is close to zero. The longer days and midnight sun during summer do not have a large effect on the energy yield of the systems since it is façade-mounted and facing south, which means that the sun is behind the modules for a significant period of each day. However, as the values for June show, the weather-related difference between years can also be substantial: the energy yield in June 2020 was 45% higher than the energy yield in June 2020.




As expected, the spring months have a quite high yield. During March and April, it is still quite cold, which increases module efficiency, and the sun angle is generally low, which is suitable for vertical system. In addition, there may still be snow on the ground, which reflects the sunlight.

3.3 Solar self-sufficiency

The monthly level of self-sufficiency (in percent) of the electric aircraft operations is shown in Fig. 5. The average self-sufficiency during these months were 0.70. With the PV energy yield in 2020, the annual self-sufficiency would have been 0.83. In June, the generated energy covered 105% pf the demand (but the self-sufficiency cannot, by definition, be higher than 1). This calculation of the net self-sufficiency assumes grid-connection of the PV system, and that energy can be exchanged with the grid at any time. Further calculations will focus on the temporal load match between solar energy and charging load at higher time resolution, and thereby the possibility to operate on solar energy without exchanging energy with the grid.



Fig. 5. The monthly level of self-sufficiency oft he electric aircraft operations, shown in percent.

Given the estimated energy requirements and the energy yield of the PV system, and disregarding the load match, the system generated enough power for 707 electric flight hours in 2020. The energy was, however, very unevenly distributed over the year, with enough for 126 flight hours in June, and only 5 in total from November to January. The average number of flight hours that it would be possible to fly with the energy from the PV system are given in Tab. 1, as average values for each month. The values for 2021 in the Tab. 1, 126.3 hours in 2020 and 86.8 hours in 2021, also shows the large difference that may occur between years.

Tab. 1. The daily flight hours that would be possible with the energy from the PV system, given as average values per month.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily flight hours 2020	2.2	18.9	75.7	99.7	110.7	126.3	83.5	80.0	54.6	52.0	2.3	0.9
Daily flight hours 2021	2.2	26.8	76.4	104.9	117.4	86.8	92.1	66.2	75.0	-	-	-

4. Discussion and conclusions

Flight schools can be early adopters of electric aircraft. In addition to a reduction in greenhouse gas emissions, introduction of electric aircraft has the potential to significantly reduce operating costs. Since airports are often well suited for solar energy installations, it is interesting to study the possible solar self-sufficiency of electric flight operations. With the current PV installation at Bardufoss, the annual energy yield in can provide around 80% of the required energy for operations with two electric aircraft, had they been used in normal training operations

For the flight school, the load-match between solar energy and flight operations, in particular electric aviation, is relatively good since most flying is done during daytime in the summer. The two electric aircraft at the flight school are not operated in cold conditions, due to the lack of de-icing capability. During the normal operation period, the average monthly self-sufficiency was 0.7. However, there may be large differences between years.

There are several possibilities to increase the solar self-sufficiency of this particular system. More PV modules could be added to the building, also at different orientations, a battery could store energy to provide direct charging without grid-connection, and the charging of the electric aircraft can be scheduled to best coincide with available solar energy.

5. Acknowledgments

The author would like to thank Terje Johan Pedersen at UTSA for insights in energy performance and operation of the electric aircraft. This work is also a part of ARC Arctic Centre for Sustainable Energy at UiT The Arctic University of Norway.

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D-06. Wearable and Consumer Product-Integrated Photovoltaics

Tracking of photovoltaic facilities based on omnidirectional sensor

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Abstract

This work describes an omnidirectional sensor that tracks the celestial vault and determines the direction of maximum solar irradiance from instantaneous measurements. For that purpose, the sensor incorporates an ex professo algorithm that considers the directions for which inter-shading between collectors would occur. Additionally, the sensor has been developed with free software and hardware, thus contributing to open science. As a result, technologists and scientists will be able to optimise the presented system by enriching and improving it. In that way, the omnidirectional sensor presented is a low-cost device that can work as a position server for dual-axis solar trackers in photovoltaic facilities, optimizing the trajectory of the trackers and the radiative capture and energy production of the PV plant. The aim is to improve the performance of the solar collectors by adapting to changing weather conditions, thus avoiding the often-complex tracking.

Keywords: Free and open-source hardware (FOSH), Sun Position Sensor, Omnidirectional Sensor, Solar Trackers, PV Plants, backtracking.

1. Introduction

In the last decades, Photovoltaics (PV) is becoming a promising source of electricity generation (Eldin et al., 2016), thanks largely to ongoing research that have led to the progress of the technology and its cost reduction. One of these lines of research is the tracking in PV plants that consist of the reorientation of the collectors towards directions that increase solar irradiance collection. Depending on the degrees of freedom of the movement, tracking can be classified into single-axis and dual-axis tracking. Collectors with single-axis tracking moves around a unique axis whereas those with dual-axis tracking moves around two different axes so that they can be oriented to any direction of the celestial vault (Lee et al., 2009). Different works have proved that energy production is higher in PV plants with tracking than in those without it (Nsengiyumva et al., 2018; Sumathi et al., 2017). For that reasons, although PV plants with tracking have higher costs than those with fixed collectors, this technology is spreading around the world and multiple research is being developed to enhance the technology and its efficiency/cost ratio (Eldin et al., 2016).

On the other hand, according to the tracking strategy, most researchers propose the astronomical tracking which is based on the movement of the Sun and is aimed in minimising the angle of solar incidence θ , that is, the angle between the solar rays and the normal to the collectors. Accordingly, astronomical tracking only considers the direct component of the irradiance and not the reflected and diffuse components which can have a significant impact depending on the atmospheric conditions, specially, on cloudy days (Duffie & Beckman, 2013).

Moreover, the astronomical tracking not only does it not consider the effect of clouds, but also the possible inter-shading between collectors which can lead to significant losses in the electricity production of PV plants. As a solution to the latter problem, different authors propose the backtracking which consists of shifting the collectors to non-shaded positions (Lorenzo et al., 2011; Narvarte & Lorenzo, 2008). In that sense, a new solar tracking/backtracking strategy has been proposed to maximize the solar irradiance collection as well as avoiding inter-shading between PV panels with dual-axis trackers (Fernández-Ahumada et al., 2020a, 2020b).

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This work merges both lines of research and presents an omnidirectional sensor that searches for the direction of maximum solar irradiance by tracking the whole celestial vault except for those directions for which inter-shading between collectors would occur. Thus, the omnidirectional sensor proposed can be used as position server in PV facilities with dual-axis trackers.

2. Design of the proposed solution

The search for irradiance optimisation of the irradiance captured by the collectors guides all the work presented here. An important improvement is to discriminate, upstream of the sky tracking, between the directions taken by the collector that would cause shading between adjacent panels. By avoiding these directions, the prototype generates a trajectory that gives a premium to collection.

Fig. 1 shows the prototype of the omnidirectional sensor proposed. It consists of a flat surface with two degrees of freedom so that the irradiance sensor located on that surface can be oriented to any direction of the celestial sphere, characterized by its azimuth (γ) and its elevation (α). The prototype has been built using additive printing on acrylonitrile butadiene styrene (ABS) filament, a thermoplastic polymer with 96°C and 93°C as distortion and softening temperatures, respectively. Additionally, the device is protected from adverse weather conditions by means of a transparent methacrylate dome.



Fig. 1: Prototype of the omnidirectional sensor

On the other hand, the device also includes a microprocessor to control the movement of the surface, the irradiance measurements, and their transmission to the solar trackers. This is the TTGO ESP32 board whose structure accumulates analogue and digital sensors and outputs, various ways of data communication both wired and wireless. With regard to the sensors, the real time clocks (DS1307) to establish the working times are noteworthy. Equally important are the calibrated PV cells dedicated to measuring the irradiance at any given moment. The motors responsible for the azimuth and elevation movements are extremely precise and are of the stepper type. Regarding the propagation of the information and, being aware of the different situations that can occur as obstacles in the direct path between sensors and receiver boards, signals ranging from 3 to 15 km can be sent. Fig. 2 shows the main electronical components.



Fig. 2: Kit of electronical components

As far as the movement of the sensor is concerned, the device incorporates the algorithm proposed by Fernández-Ahumada et al. (2020a, 2020b) to determine the direction for which inter-shading between collectors would occur. Thus, the sensor scans the whole celestial vault measuring the solar irradiance, except for those directions with inter-shading. From these instantaneous measurements, the orientation with maximum irradiance and not shading is determined and its azimuth (γ) and elevation (α) angles are made available to the solar trackers so that the PV collectors can be orientated towards the position of maximum capture.

The complete architecture of the device has been developed with Free and Open-Source hardware (FOSH) and IoT technologies. Thus, the sensor proposed becomes an economically competitive tilt and azimuth server to favor the optimization of energy production in PV plants with dual-axis trackers.

3. Results

Figs. 3, 4, 5 and 6 shows the representation of the data obtained by the proposed omnidirectional sensor at different times of the year in a Lambert projection hemispheric diagram mode for the "Peñarroya I" PV plant, situated at a location of 38.299224° N latitude and -5.303114° longitude. The grey region of the figure represents the orientations which imply inter-shading between PV collectors while the blue region represents the directions with no inter-shading. Thus, irradiance measurements (in W/m²), represented in these figures by iso-level curves (grey lines), are only made in the blue region.



Fig. 3. Data registered by the omnidirectional sensor proposed on June 21st at 15:48 pm (True Solar Time).



Fig. 4. Data registered by the omnidirectional sensor proposed on December 21st at 8:24 am (True Solar Time).



Fig. 5. Data registered by the omnidirectional sensor proposed on December 21st at 15:24 (True Solar Time).



Fig. 6. Data registered by the omnidirectional sensor proposed on June 21st at 7:24 am (True Solar Time).

4. Conclusions

The present work presents the design and manufacture of an omnidirectional sensor to determine the orientation of the collectors of a dual-axis PV plant that guarantees maximum solar irradiance capture with no inter-shading between collectors. The device has been developed as Free and open-source hardware (FOSH) contributing to the advance of open science and the improvement of the PV tracking technology. It

is remarkable that the device continuously calculates the locations that generate shading between adjacent collectors. The system also avoids the continuous calculation of the direction of maximum irradiance of the astronomical method and replaces it with internally implemented methodologies for tracking and backtracking.

Thus, the omnidirectional sensor presented will enable the optimization of the energy production in PV plants with dual-axis trackers.

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E-01. CSP and CST Systems

Superheater Design Assessment for Flexible Solar Tower Plants

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Abstract

The steam generator failure is one of the main causes of unavailability of commercial solar tower plants. The superheater, as the point most susceptible to failure due to creep-fatigue damage, should be carefully analyzed to assure suitable reliability levels. For that reason, in this work, a novel superheater based on the header-type design is selected for a structural comparison study against to the conventional design consisting in a shell-and-tube hairpin-type superheater.

Keywords: Steam generator, Creep-fatigue, Lifetime, Transient operation

1. Introduction

Solar tower plants have become a renewable solution able to play the role of load following plants like combined cycles (Mehos et al., 2017), which have a key role in modern electricity markets with high penetration of variable renewable energies. In this context, solar power plants are pushed to operate with fast start-ups and/or load changes to meet users demand and counter-balance grid stability issues. However, aggressive operations lead to an increase of the fatigue damage which may be combined with creep, leading to an extraordinary lifetime reduction on critical components like superheaters. Therefore, the correct selection of the superheater design has become a critical step to achieve the required levels of reliability and flexibility of solar tower plants.

The superheater, as a critical point of the steam generator system (SGS), has a high influence on the performance and forced outages of the plant. According to the Concentrating Solar Power Best Practices Study (Mehos et al., 2020), the system with the highest number of issues occurred in commercial solar tower plants was related to the steam generator reliability and design. Figure 1 shows the main issues reported plotted by priority and number of occurrences. As it can be noticed, the ones that appear at the upper-right quadrant are the main issues for the industry. This also has further effects in costs and maintenance, which appear to be greater than predicted in previous studies. Numerous problems related to reliability and availability have occurred due to the conventional steam generator design based on shell-and-tubes with flat tube sheets. For that reason, a novel model of heat exchanger called Header-type is going to be analyzed.

In the open literature can be found some works focused on the structural integrity assessment of steam generators for concentrating solar power plants (Ferruzza et al., 2019; González-Gómez et al., 2019, 2018). In the case of parabolic trough plants, the main mechanism of damage is fatigue due to the low working temperatures and the used standards were the EN-12952-3 and the ASME Section VIII-Div2. The high working temperatures of solar tower plants lead to a significant creep damage which may be combined with fatigue, and at such conditions the recommended code is ASME III-Subsection NH.

2. Case of study

A conventional molten-salt solar tower plant of 110 MWe Rankine cycle has been selected for the analysis. The main plant layout can be studied in Figure 2, where the main focus should be the steam generator. The steam generator consists of an indirect steam generator system where the hot fluid is molten salt (i.e., 60% NaNO3 and 40% KNO3) which is heated at the receiver (R) using solar radiation and then enters the steam generator system when it is required. It is stored in both cold and hot tanks (CT, HT). The cold fluid is water/steam which flows through the SGS in order to produce steam and expand at the power block. The steam generator is formed by four heat exchangers: superheater (SH), reheater (RH), evaporator (EV) and preheater (PH). Water/steam and salt properties are calculated according to (Wagner and Kretzschmar, 2008) and (NREL, 2009) respectively.

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Fig. 1: Main issues reported at central receiver CSP plants plotted by priority and number of occurrences (Mehos et al., 2020)



Fig 2. Plant layout.

Besides the commonly-used Hairpin-type, a novel model of heat exchanger called Header-type is going to be studied as well. The working system and its geometry can be seen in Figure 3. The water or steam enters the heat exchanger through the inlet header, flows through the different coils and goes out across the outlet header. This process happens in multiple layers. On the other hand, the salt flows on the shell side between the tube bundle. Header-type superheater is going to be analysed against the Hairpin-type to confirm its excellent performance shown in different studies (Mehos et al., 2020) as there is no highly reliable data about this topic. Its manufacturer, Aalborg CSP (Aalborg CSP, 2021) reported no leakage in commercial service. In order to obtain the design and main specifications of the SGS, 4 individual optimizations are carried out. The geometry obtained for both hairpin-

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type and header-type are presented in Table 1.

From creep-fatigue point of view the most critical component is the superheater. This is because the superheater has to withstand the highest temperatures, which are combined with high temperature gradients which induce large stress variations and fatigue, and all of this may lead to a premature creep-fatigue failure. In Figure 3 the potential critical points of the superheater designs selected for this study are shown.



Fig. 3: Selected superheater designs and critical points. Right: hairpin-type; Left: header-type (Aalborg CSP, 2021).

Tab. 1. Geometry of both hairpin-type and header-type superheaters.

	Hairpin-type	Header-type
Head/header outer diameter (mm)	842	466
Head/header thickness (mm)	130	66.2
Nozzle/tube outer diameter (mm)	404	25
Nozzle/tube thickness (mm)	77	3.1

Once the design of the SH is known, the thermo-mechanical analysis is implemented. The operation of the steam generator selected for the study is the warm startup (González-Gómez et al., 2019). The initial temperature of the heat exchanger is 290°C which is the set point to prevent the salt from freezing. The initial pressure matches the saturation pressure at 290°C, i.e. 74 bar. The main trends of the temperature and pressure for the superheater are illustrated in Figure 4.



Fig. 4: Temperature and pressure evolution in the superheater during steam generator startup.

3. Methodology

Before performing the creep-fatigue analysis, it is necessary to determine the thermal and pressure stresses occurred during the transient operation of the steam generator. To that end, the methodology presented in (González-Gómez et al., 2017) is used to determine the stress in hot spots of the superheater like header and tube joints as point P shown in Figure 5 in the case of header -type SH. Thermal stress σ^T is obtained according to the European standard EN 12952-3:

$$\sigma^{T} = \frac{\beta \cdot E}{1 - v} \cdot \left(T_{m} - T_{r=r_{i}}\right) \quad (\text{eq.1})$$

where β is the thermal expansion coefficient, *E* is the Young's modulus, *v* is the Poisson ratio, T_m is the mean integral material temperature and $T_{r=r_i}$ the inner wall temperature. These two last parameters can be deducted from solving the cylindrical heat diffusion equation restricted only in the radial direction with the initial and boundary conditions shown in eq. 2, using the Crank-Nicholson method (Esfandiari, 2017):

$$\begin{cases} \frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \\ T(r,0) = T_0 \\ -k \frac{\partial T}{\partial r} \Big|_{r=r_i} = h_i \cdot (T_i - T(r_i,t)) \\ -k \frac{\partial T}{\partial r} \Big|_{r=r_o} = h_o \cdot (T(r_o,t) - T_o) \end{cases}$$
(eq.2)

The header side heat transfer coefficient h_i , is obtained according to Gnielinski correlation (Serth et al., 2014). On the other hand, the shell side heat transfer coefficient is calculated according to Hilpert correlation (Bergman et al., 2011).

The mechanical stress σ^P is calculated according to EN 12952-3 as well, where P_i is the internal pressure existing in the SH. D_m and e are the average diameter and thickness of the header, respectively:

$$\sigma^P = P_i \cdot \frac{D_m}{2 \cdot e} \tag{eq.3}$$

Once both thermal and mechanical stresses are deducted, the total stress appearing at point P is calculated applying two thermal and mechanical stress concentration factors, α_T and α_M , respectively, according to the European standard:

$$\sigma = \alpha_M \cdot \sigma^P + \alpha_T \cdot \sigma^T \qquad (\text{eq.4})$$



Fig. 5: Tube-header junction

2.1 Creep damage

In first place, the elastic-plastic stress σ is deducted according to the Neuber's equation where ε_{offset} is calculated as shown in (Kalnins, 2016):

$$\sigma^{E} \cdot \varepsilon^{E} = \frac{\sigma^{2}}{E} + \sigma \cdot \left(\frac{\sigma}{K'}\right)^{1/n'} - \sigma \cdot \varepsilon_{offset} \qquad (\text{eq.5})$$

K' and n' are experimental parameters whose values are summarized in Table 2 which have been obtained by fitting from the experimental data available in (Stoppato et al., 2012), according to the cyclic stress-strain curve, which takes into account the cyclic hardening of the steel.

Tab. 2. Parameters K' and n' for 321H stainless steel according to (Stoppato et al.,	2012).
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Matarial		Cyclic stress/strain curve		
Material	Temperature (C)	K' (MPa)	n' (-)	
22111 staiplass staal	540	1928	0.361	
321H stanness steel	20	2082	0.317	

In the Header-type calculation process, the value of elastic-plastic stress should be corrected as mentioned in (Stoppato et al., 2012) multiplying it by a weld strength reduction factor equal to 1.05 according to the ASME Code (ASME, 2004).

Finally, the creep damage is obtained as the summation of the ratios between the duration of the time intervals at which the time is discretized along the lifetime (a total of N) and the time to rupture, t_R :

$$D_c = \sum_{i=1}^{N} \frac{\Delta t_i}{t_{R,i}(\sigma_i, T_i)}$$
(eq.7)

The creep damage is calculated considering 6000 hours per year. The time to rupture is obtained from the European Creep Collaborative Committee datasheets (ECCC, 2005).

2.2 Fatigue Damage

The fatigue damage is calculated according to what it is proposed in (Stoppato et al., 2012). The plastic strain is estimated thanks to the Neuber's rule (eq. 5). Then, the number of cycles N_a to failure is calculated according to the experimental Manson-Coffin curve. In the Header-type analysis, the recommended number of cycles is one half of the N_a obtained due to the welding between tubes and header effect.

Lastly, the fatigue damage is due to the M fatigue cycles during the lifetime and the number of allowable cycles in which these strain ranges result individually, N_a :

$$D_f = \sum_{j=1}^{M} \frac{N_j}{N_{a,j}(\varepsilon_j, T_j)}$$
(eq.8)

The number of startups considered to estimate the fatigue damage is set to 300 per year.

2.3 Lifetime calculation. Creep-Fatigue interaction

The failure criterion is set by the allowable limit of damage (D_L) according to the ASME Code (ASME, 2004) for the stainless steel 304 and 316 interaction bilinear rule: (1,0), (0.3,0.3) and (0,1). This approximation is taken since there is no available experimental data about creep-fatigue interaction of 321H stainless steel and following the approach used in (Stoppato et al., 2012). The sum of creep and fatigue damages must be lower than the maximum allowable limit of damage D_L as:

$$D_f + D_c \le D_L \tag{eq.9}$$

Lifetime of the superheater is estimated by an iterative process until the total damage set as the sum of creep and fatigue damage converges into the D_L .

4. Discussion of the results

The temporal evolution of the pressure, the thermal and the total stresses during the startup for both designs are depicted in Figure 6. As can be seen, the high thickness of the head for the hairpin-type involves a high thermal inertia and then a larger thermal stress variation is obtained compared to the header-type. The positive thermal stress of the header-type is due to the convective external boundary condition of the hot salt instead of insulated as is the case of the hairpin-type. The steady-state stresses, which are the most important to calculate the creep damage, are around 153 MPa and 170 MPa for the header-type and hairpin-type, respectively.



Fig. 6: Stress analysis results.

Figure 7 illustrates the results of the finite element transient thermal analysis at the maximum thermal stress time instant. As can be seen, the temperature difference between the inner and outer wall is around 100 °C for hairpin-type and around 15°C for header-type. This great difference is mainly caused by the greater wall thickness of the hairpin-type head over the header thickness. Another important differential factor is the external boundary condition, while the external surface of the header is exposed to the salt flow, the external surface of the hairpin-type head is insulated.



Fig. 7: Finite element transient thermal analysis results.

The creep damage, the fatigue damage, and the lifetime results are depicted in Figure 8. The results show that the creep is the dominant mechanism of damage for the header-type whereas in the hairpin-type both damages have a similar order of magnitude leading to a damage limit value lower than the unity, $D_L < 1$. The results of the lifetime are 15 years and 48 years for the hairpin-type and header-type, respectively. Finally, the comparison study reveals that the header-type presents an important lifetime increase, thus becoming an interesting option to enhance the reliability of the steam generator.





5. Conclusions

The results presented in this document give hints that could illustrate how the header-type design develops an upgraded performance when compared to the hairpin-type, under high temperature and pressure working conditions. Based on the results showed above, the following conclusions are obtained:

- Header-type superheater design reduces 6.6 times the maximum temperature difference between inner and outer walls during a daily start-up.
- The temperature difference reduction is mainly due to the lower metal wall thickness of the header-type design. Consequently, the fatigue damage is practically eliminated in the hot header of the header-type superheater.
- The creep damage appears to be a key factor to estimate the lifetime of the header-type superheater. In contrast, the combination of creep-fatigue damages becomes fatal for hairpin-type superheater obtaining lifetimes much lower than typcial lifetime design targets.
- Header-type superheater shows a lifetime 3 times higher than hairpin-type superheater.
- The good structural results obtained by the header-type superheater suggest that it would be a promising option for solar tower plants operated as "peaker plant".

6. Acknowledgements

This research is partially funded by the Madrid Government (Comunidad de Madrid) under the project ZEROGASPAIN-CM-UC3M (2020/00033/002) belonging to the program of Multiannual Agreement with UC3M in the line of "Fostering Young Doctors Research" and in the context of the V PRICIT (Regional Programme of Research and Technological Innovation, the Spanish government under the project RTI2018-096664-B-C21 (MICINN/FEDER, UE) and the scholarship "Ayudas para la formación del profesorado universitario" (FPU-02361) awarded by the Spanish Ministerio de Educación, Cultura y Deporte (MECD).

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Abbreviations			
ASME	American Society of Mechanical Engineers	Н	hours of operation (hours), dwell time period (hours)
CT	Cold Tank	h	heat transfer coefficient (W/m ² K)
CSP	Concentrated solar power	K'	strain hardening parameter (MPa)
EV	Evaporator	Κ	thermal conductivity (W/mK)
FW	Feed water	Na	number of allowable cycles
HP	High pressure	n'	strain hardening exponent
HT	Hot tank	P_i	internal pressure (Pa)
LP	Low pressure	r	radial direction (m)
PH	Preheater	r _e	outer radius (m)
R	Receiver	r _i	inner radius (m)
RH	Reheater	Т	Temperature (°C)
SGS	Steam Generator System	t	time (s)
SH	Superheater	t_R	time to rupture (hours)

Appendix: Nomenclature

Symbols		Greek Symbols	
D_m	mean diameter (m)	α	stress concentration factor, thermal
Dc	creep damage		diffusivity (m ² /s)
D_f	fatigue damage	в	thermal expansion coefficient (K ⁻¹)
D_L	damage limit	ν ν	Poisson's ratio
Ε	Young modulus (MPa)	σ	stress (MPa)
е	thickness (m)	ε	strain
		E _{offset}	strain offset

Creep and fatigue damage assessment for molten-salt central receivers

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Abstract

The receiver of the solar power tower plants is one of the subsystems under extremely demanding working conditions: the high heat fluxes concentrated onto its surface by the heliostat field are responsible for the receiver tubes high temepratures and thermal and mechanical stresses. On the one hand, the receiver tubes suffer from creep damage during hold periods under these conditions. On the other hand, the cyclic operation of the receiver at these high temperatures and stresses, caused by cloud passages and night periods interruptions, is responsible for the fatigue damage on the tubes. Yet, the lack of consensus in the molten-salt receiver field of study, with works neglecting either one damage mechanism or the other, motivates this study, in which a preliminary analysis on the creep and fatigue damages share in a molten-salt central receiver is carried out for different days of the year and direct normal irradiance configurations. The goal is to determine the possible damage mechanism trends during the receiver operation going from clear days to others with intermittent interruptions at high frequencies. The results show that, with a reasonable control of the receiver operation, the creep is the most relevant cause of receiver damage, opposite to fatigue, which would only be a matter of concern during days with high intermittent DNI and no regard for the flux incident of the receiver.

Keywords: External central receiver, Creep-fatigue, Lifetime, Transient operation.

1. Introduction

Solar power tower plant receivers are one of the most critical subsystems of these facilities, being subjected to high non-uniform heat fluxes coming from the heliostat field, which result in high tube temperatures as well as high thermal and mechanical stresses. Under these conditions, the receiver transient operation, caused by the daily cycles and cloud passages, is responsible for fatigue damage on these tubes, while during hold periods, the creep damage becomes a concening damage mechanism.

Early-day analysis of the damage inflicted to molten-salt receivers during their regular operation were based on the ASME Code Case N-47 (American Society of Mechanical Engineers, 1980), suitable for nuclear applications. These studies were mainly focused on the fatigue damage caused by the receiver cyclic operation (Grossman and Jones, 1990) rather than the creep damage one (hold periods at high temprature), with some studies even considering the creep damage negligible (Babcock & Wilcox Company, 1984; Kistler, 1987). The N-47 was simplified by Berman et al. (1979) to make it more suitable for its application in concentrating solar power technologies; such simplification was followed in the work of Narayanan et al. (1985), regarding both the creep and fatigue damages. However, the creep fatigue analysis performed by González-Gómez et al. (2021), which introduced a methodology to take into account commonly-disregarded aspects such as the stress relaxation or the plasticity effects, resulted in greater creep, with fatigue being negligible, although it was performed for clear-sky conditions.

In addition, recent works contemplating the use of alternative heat transfer fluids (HTFs), which are oriented to an operation with higher temperatures than molten-salts, showed a consensus in the fact that the creep damage mechanisim was the most prominent one: Fork et al. (2012) studied an air receiver, Neises et al. (2014) a receiver using sCO_2 as HTF and Conroy et al., (2018) analysed multiple aspects of a billboard sodium receiver.

Thus, in sight of the gap found for the range of temperatures of molten-salt receivers between the results of earlyday works, wich used quite simplified approaches, and the more recent ones, wich deal with a more detailed creepdamage calculation, this work aims to obtain preliminary results on the investigation of the creep and fatigue damages share under the transient conditions.

2. Methodology

The calculation procedure for the receiver analysis comprehends several models that deal from the receiver interaction with the heliostat field to the damages and lifetime analysis of its tubes. The required models for such integral analysis are detailed below.

The heat flux distribution on the receiver is obtained with the optical model proposed by Sánchez-González and Santana (2015), where the heliostat field aiming strategy, k, is selected: it can be from an equatorial strategy, (the target is the middle length of the receiver), to an open one (aiming towards both receiver ends). The equatorial strategy results in high peak fluxes, providing a greater optical efficiency and power production, although such fluxes could damage the receiver tubes in excess; on the other hand, the open strategies decrease the peak flux but result in a lower efficiency. In addition, a minimum solar height of 10° is required (Falcone, 1986) to evaluate the flux on the receiver. The goal is to avoid great optical losses in the heliostat field due to shading and blocking of heliostats or the cosine effect, which are more prominent near sunrise and sunset. Hence, the heliostat field aiming strategy is selected as equatorial as possible for the time intervals in which the clear-sky days under study are discretized. Nevertheless, the film temperature and the stress reset limit (Becht IV, 2011) are watched in the models presented below in order to avoid the tubes accelerated corrosion and to guarantee the global stress relaxation, respectively, which may require modifying the aiming strategy as the day progresses in order to not surpass these limits at any time. This results in the scheduled heliostat field aiming strategy for the clear day. During periods of lower DNI with respect to the expected clear-sky one, the heliostat field aiming strategy remains the same as the scheduled for the clear day, given the uncertainty that characterizes the cloud transients that decrease such DNI.

Then, the thermal model for the receiver is the one proposed by Rodríguez-Sánchez et al. (2014) which allows to obtain the tubes temperatures, including the film temperature that should be watched. In such thermal model, the receiver tubes are discretized in axial and circumferential divisions, and just one tube representative per panel is regarded. Two modes are contemplated regarding the thermal model: during clear-sky conditions, the HTF mass flow is adjusted so its outlet temperature meets the desired value (565°C), while during transient periods the mass flow used is the clear-sky scheduled ones and the HTF outlet temperature fluctuates in lower values than the objective one.

With the tubes temperatures, the elastic stresses and strains (σ_{eq}^E , ε_{eq}^E) are calculated with the model presented by Laporte-Azcué et al. (2020), which takes into account the temperature dependence of the tube material properties, providing more accurate results than the case of constant properties. Here it must be checked that the elastic stresses are below the stress reset limit:

$$S_{SR} = S_{y,cold} + S_H, \qquad (eq.1)$$

where $S_{y,cold}$ is the yield strength at room temperature and S_H is the hot relaxation strength, typically taken as 1.25 times the allowable stress, *S*, established by the ASME BPVC, Section II Part D (American Society of Mechanical Engineers, 2010). In addition, since the stress reset limit is just below the twice yield strength, the plastic shakedown regime is also avoided.

Lastly, the damage model proposed by (González-Gómez et al., 2021) is employed. The initial step is to obtain the elastic-plastic stresses and strains (σ_{eq} , ε_{eq}) by means of the elastic ones. Then, the stress relaxation of the tubes is also considered for a stabilization time, t_{stab} , of 30 hours (González-Gómez et al., 2021) since the global stress relaxation phenomenon is guaranteed by not surpassing the stress reset limit:

$$\sigma_{relax} = \sigma_{eq} - E\left[\left(\sigma_{eq}/E \right)^{1-n_r} - (1-n_r)AE^{n_r} \exp(-Q/(RT)) \frac{t_{stab}^{m+1}}{m+1} \right]^{\frac{1}{1-n_r}}.$$
 (eq.2)

Here Q stands for the creep activation energy (J/mol), R is the ideal gases constant (J/(molK)) and E is the Young modulus (Pa). The *m* coefficient is the creep exponent that, when set to zero gives a simple Norton equation, allowing to consider the secondary creep rates, n_r is the creep-strain model coefficient and A is the stress relaxation constant (1/(Paⁿrs)). The stabilization time is expressed in seconds in eq. 2.

Thus, the creep stress results as

$$\sigma_c = (\sigma_{eq} - \sigma_{relax})/C', \qquad (eq.3)$$

where C' is a safety factor set as 0.9, suitable for inelastic analysis of CSP technologies (Barua et al., 2020). If, as the result of such coefficient, the creep stress is greater than the equivalent one, the latter is taken instead in order to

avoid an excessive level of conservatism. The rupture time is then calculated with the Mendelson-Roberts-Manson parametrization:

$$\log_{10}(t_R) = \beta_0 + \beta_1 \frac{1}{T} + \beta_2 \log_{10}(\sigma_c) + \beta_3 \log_{10}(\sigma_c) \frac{1}{T} \quad (\text{eq.4})$$

Being T the tubes temperature in Kelvin and β the coefficients of the parametrization, which depend on the material selected (Laporte-Azcué et al., 2021a). In eq. 4 the creep stress is introduced in MPa.

Then, the creep damage during day i is obtained as the summation of the ratios between the duration of the time intervals at which the day is discretized (a total of J) over the number of hours resulting from the rupture time calculation at every time interval:

$$d_{c,i} = \sum_{j=1}^{J_i} \frac{\Delta t}{t_{R,j}}.$$
 (eq.5)

On the other hand, the fatigue damage is due to the M fatigue cycles during the day, N, and the number of allowable cycles in which these strain ranges result individually, N_a :

$$d_{f,i} = \sum_{m=1}^{M,i} \frac{N_m}{N_{a,m}}.$$
 (eq.6)

The number of allowable cycles of the material depends on the equivalent elastic-plastic strain range as:

$$\frac{\Delta\varepsilon_{eq}}{2} = \frac{\Delta\varepsilon_{eq}^E}{2} + \frac{\Delta\varepsilon_{eq}^P}{2} = \frac{\sigma_f'}{E} N_a^{-c_1} + \varepsilon_f' N_a^{-c_2}.$$
 (eq.7)

The exponents and coefficients of such expression also depend on the material used. In order to take into account the possible creep-fatigue interaction effects, such N_a is modified with a reduction factor of 4, prior its use in Equation 6 (Radke et al., 2017). Moreover, the strain range of Equation 7 is altered by a x2 factor and constitutes a way of taking into account the effects of the load history, the size, the material variability and the surface finish of the specimen under study (O. K., Chopra; W. J., 2003; Radke et al., 2017).

With all of the above, the receiver lifetime is obtained by means of the equivalent operating days (EODs), calculated for a single day as:

$$D_L = d_c EODs + d_f EODs \rightarrow EODs = \frac{D_L}{d_c + d_f}$$
, (eq.8)

which satisfies that the damage limit, D_L , is not surpassed by the summation of the total creep and fatigue damages $(D_L \ge D_c + D_f)$. In this case, the linear damage summation model has been considered, which is equivalent to a linear interaction of the creep and fatigue damages, with their sum always being equal to one.

The interaction among the models used and the thermal and mechanical limitations involving them which have been regarded are presented in Figure 1.



Fig. 1: Calculation procedure with the models employed.

3. System description

3.1. Heliostat field and receiver configuration

The heliostat field selected is located in Seville, Spain at a latitude of 37.56° . Its layout corresponds to the Gemasolar plant one, with 2,650 heliostats of 115.8 m² of effective mirror surface each, which gives a 306,605 m² of mirror area in total (Burgaleta et al., 2011).

On the other hand, an external tubular central receiver of cylindrical shape, depicted in Figure 2, is the main object of this study. Such receiver is constituted by 18 identical panels that surround the cylindrical frame of 8.5 m of diameter holding them, which is placed at the top of a 130 m height tower. The panels are constituted by vertically disposed tubes of length 10.5 m, their external diameter is 2.24 cm, being 1.2 mm thick. Their separation within a certain panel is initially set at the 8% of their external diameter, although such distance is adjusted so an integer number of tubes fit while being evenly spaced. Thus, giving the number of panels, the receiver frame diameter, the tubes outer diameter and their separation, the number of tubes per panel results in 61. These tubes are coated with a black Pyromark painting in order to increase their absorptivity, while the base frame -that behaves as a refractory wall- is covered with a high reflectivity paint so the greatest amount of radiation is reflected to the tubes. The material selected in this work for the tubes manufacturing is Haynes 230 since it has been proven to be one of the best alternatives in terms of endurance and thermal power/cost ratio (Laporte-Azcué et al., 2021a), outperforming other materials used in the field, such as alloy 316H, Inconel 625 or Incoloy 800H; in addition, it showed a linear interaction of the total creep and fatigue damages, as assumed in the linear damage summation model, in the experiments performed by Chen et al. (2013). Haynes 230 thermal and mechanical properties are available as temperature dependent in the ASME BPVC Section II, Part D (American Society of Mechanical Engineers, 2010), while its creep and fatigue damage coefficients are compiled in (González-Gómez et al., 2021), which are essential to undertake the receiver lifetime analysis. The tubes are guided by a series of welded supports, called clips, in order to avoid their excessive deflection, which could cause collision between adjacent tubes. For this study, an infinite number of clips is selected, equivalent to the generalized plane strain conditions.



Fig 2: Schematic representation of the receiver under study

The solar salt (NaNO₃-KNO₃) used as HTF is divided into two parallel flow paths, symmetrical with respect the N-S direction, with the inlet of the cold fluid in the northern panels and the outlet of the hot HTF being located in the southern ones (panels 9E and 9W for each flow path, as depicted in Figure 2). The HTF flows through the panels of each path in a serpentine-like way, alternating upwards and downwards flow. The combination of HTF and tube material selected results in a maximum allowable film temperature of 650 °C (McConohy and Kruizenga, 2014).

3.2. Days under study and direct normal irradiance cases

Three days are selected to perform the study: the spring equinox (Julian day 81), the summer solstice (day 172) and the winter one (355). Their clear-sky DNI (Figure 3) is obtained according to the Daneshyar-Paltridge-Proctor model (Reno et al., 2012). The different start and final time instants depicted for each day is related to the 10° sun altitude condition set in the heliostat field optical model described in Section 2.

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Fig. 3: Clear-sky DNI for the days analyzed (left) and DNI cases during the spring equinox morning hours (right).

For the scheduled aiming strategy, the receiver operation is subject to a minimum heat flux on the receiver equal or above 40 kw/m^2 . On the other hand, despite control operation algorithms are not contemplated in this preliminary analysis, the receiver is kept in preheating conditions if the average heat flux with the scheduled aiming strategy is also equal or above 40 kW/m^2 ; that way, the range between 12 and 36 kW/m² (Vant-Hull, 2002) could be achieved with aiming strategies oriented to the preheat mode. Thus, the contribution of the creep and fatigue damages is addressed by studying the three selected days under four different DNI scenarios, depicted in Figure 3 (right side) for the spring equinox:

- The first one, case A, is the clear sky day.
- Then, to properly sense the fatigue damage, the DNI fluctuates as the time intervals progress between the clear-sky one and the minimum DNI that guarantees the receiver operation conditions (case B).
- Case C is under a DNI going alternatively between the clear-sky one and a DNI below the operation conditions but guaranteeing the preheat ones.
- Lastly, as an extreme fatigue situation, a day with its DNI fluctuating between the clear-sky DNI and zero, case D.

For these scenarios, the days have been discretized in time intervals of 5 minutes, since they offer a good compromise between computational cost and accuracy in the receiver lifetime estimation (Laporte-Azcué et al., 2021b).

4. Results and discussion

The maximum creep and fatigue damages for the eastern flow path of the receiver are presented for all its panels in Figures 4 and 5, respectively. The western half is omitted since the DNIs studied are symmetrical with respect solar-noon, resulting in the same outcome for both receiver halves.



Regarding the $d_{c,max}$, the clear-sky scenario is the critical one, with the creep damage for cases B, C and D dropping almost the same amount for the three selected days (Spring equinox, Winter solstice and Summer solstice), around half of the clear-sky creep damage. These two facts are particularly relevant since it means that the creep damage during situations far from the clear-sky conditions does not depend on the operation mode and is almost negligible in these three scenarios: whether the receiver operates with periods of a minimum heat flux at the verge of ceasing its operation, or periods where is kept preheating, the creep damage is negligible since the total during the day is similar to one for the case with those periods resulting in the receiver completely shut down.



Fig. 5: Maximum fatigue damage during a) day 81, b) day 172 and c) day 355. Conclusions

On the contrary, Figure 5 shows that the $d_{f,max}$ of the case with extreme fluctuations (D) is one order of magnitude greater than the one obtained for cases A and B and over 5 times greater than case C; moreover, such fatigue damage is also one order of magnitude greater than its corresponding creep damage. In case C, the $d_{f,max}$ is twice its $d_{c,max}$. Lastly, for cases A and B, it is one order of magnitude lower than the creep damage. Thus, looking at the case B, with the same number of fatigue cycles than the cases C and D, the setting of the minimum heat flux on the receiver at 40 kW/m² seems reasonable: the fatigue damage due to the maximum number of cycles that can occur while guaranteeing the operation during the whole day is not particularly great –just slightly above the fatigue damage of the clear day- and, on the other hand, the creep damage is considerably reduced due to the drop of the receiver temperatures and stresses at such DNI. Additionally, to include the preheating conditions (case C) opposite to completely shut down the receiver (case D) helps reducing the fatigue damage. Nevertheless, in sight of the results obtained, setting a forecast window to decide whether to resume operation or not is advised as a good practice in order to reduce even more the fatigue damage.

As the result of the maximum creep and fatigue damages, the receiver lifetime is estimated for the three days individually, Figure 6, assuming the receiver would only work that way during its lifetime, in order to get an initial approximation on how these damages translate in terms of the receiver endurance. For a certain day, while the southern receiver panels have almost the same lifetime regardless the DNI case, divergences are observed in the northern ones, which happen to be the least enduring panels. Looking at these northern panels, the extreme fatigue scenario -and unrealistic for the best practice standards- results in the earliest receiver failure. Case C is the following one when looking at the first panel due to its high fatigue damage with respect cases A and B, although for the rest of the panels is similar to case B. Then, the clear-sky day is penalized by the high creep damage it must endure during the whole day, not benefitting from the descend on its temperatures and thermal stresses due to transient interruptions. Thus, the panels last longer throughout the whole receiver in case B, which suffers momentary descends in the creep damage but without presenting compromising fatigue levels. Nevertheless, the potential energy production would be lower than during the clear-sky conditions.



Fig 6: Lifetime estimation of the receiver panels considering the isolated damage contribution of a) day 81, b) day 172 and c) day 355.

Among the three days, the most critical in terms of creep damage is the spring equinox (see Figure 4), although it should be noted that, disregarding any potential limit set by the thermal storage system filling, the winter solstice presents an operation window over two hours shorter than the spring day. The summer solstice, being the day with the longest operation, suffers the lowest creep damage in the first receiver panel (the critical one the other two days), although it has the most damaged panels in terms of creep once passed the flow path half. The higher DNI of this day imposes the need to switch the aiming strategies earlier in the morning and later in the afternoon and thus, decreases the peak flux on the receiver, which explains why the creep damage is not that high despite operating two hours and a half more than the day 81 and over 4 hours and 40 minutes than day 355 during the clear-sky scenarios. The fatigue damage is very similar with the exception of the extreme fatigue case during the winter solstice, being slightly lesser.

5. Conclusions

This preliminary analysis of the damage mechanisms on a molten-salt solar central receiver during different transient conditions assumptions has the objective to test the receiver in critical conditions, from a day with an exceptional clear conditions to another one with high frequency fluctuations of its DNI.

It is observed that creep is the main damage mechanism even during days with small transients (case B) that allow a continuous operation, although the creep during low DNI periods could be considered negligible. Moreover, the additional fatigue damage caused by such small transients is barely noticeable since the fatigue damage comparison of cases A (clear-sky day) and B is highly resembling. From there, the fatigue damage increases with the amplitude of the strain, being advisable to keep the tubes preheating (case C) in order to avoid the excess of fatigue damage found when completely shutting down the receiver (case D), which would result in an excessively short receiver lifetime. The clear-sky assumption would be a conservative approach when obtaining the receiver lifetime due to the greater overall creep damage, while a quick calculation of the fatigue based on such clear-sky day could be admissible.

Overall, the results of the comparison carried out suggest that when keeping a reasonable control level of the receiver operation, as expected in any real facility of this kind, the creep dominates over the fatigue damage, even considering aspects such as the stress relaxation (relevant for the creep damage) or the tubes history and sample size (fatigue damage). It would be advisable to expand this preliminary study in future works, analyzing the creep/fatigue share under real DNI cases, implementing a DNI control on the receiver in order to start it up only according to its real necessities, so a more precise extent of the creep/fatigue share could be determined.

6. Acknowledgements

This research is partially funded by the scholarship "Ayudas para la formación del profesorado universitario" (FPU-02361) awarded by the Spanish Ministerio de Educación, Cultura y Deporte (MECD), the Spanish government under the project RTI2018-096664-B-C21 (MICINN/FEDER, UE) and the call "Programa de apoyo a la realización de proyectos interdisciplinares de I+D para jóvenes investigadores de la Universidad Carlos III de Madrid 2019-2020", under the projects RETOrenovable-CM-UC3M and ZEROGASPAIN-CM-UC3M, funded on the frame of the Convenio Plurianual Comunidad de Madrid- Universidad Carlos III de Madrid.

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Optimization and Techno-Economic Assessment of 50 MWe Solar Tower Power Plant for Different Climatic Zones in Pakistan

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Abstract

Optimal sizing of solar tower power (STP) plant with full load thermal energy storage (TES) hours and solar multiple (SM) is a challenge to reduce the overall cost of the system and increase system outputs. The growing trends of STP technology worldwide due to its higher efficiency make it an attractive option for several potential sites in Pakistan. The primary aim of this study is to check the effect of SM, solar field, TES hours and design point irradiance on the capacity factor (CF), annual energy generation (AEG) and levelized cost of electricity (LCOE) for STP plant with air-cooled and no backup system. The multi-objective optimization, comparison, and feasibility analysis of 50MW concentrated STP plant were performed at nine stations, receiving more than 1600 kWh/m² average annual direct normal irradiance (DNI), using the economic model of Pakistan. The solar radiation data of nine stations, used for performance analysis, was measured by ESMAP of the world bank. The techno-economic evaluation of the initial and optimized designs revealed that the optimized design has higher CF, AEG, and lower LCOE. It was found that LCOE depends on the SM, TES hours and DNI value of the location. The results indicate that the least LCOE under the optimized configuration of the proposed plant for Khuzdar is 6.67 ¢/kWh, followed by Quetta 7.25 ¢/kWh for Salt 1 (60% NaNO₃ and 40% KNO₃). It is, therefore, concluded that Khuzdar is the best-suited place for STP plant installation, followed by Quetta, and Lahore is the least suitable out of the nine stations.

Keywords: Solar Tower power, Design-point DNI, Solar Multiple, System Advisory Model (SAM)

1. Introduction

Energy demand is increasing rapidly all over the world with population and industrial growth. The environmental issues, high electricity prices and continuous depletion of fossil fuel-based resources have forced the world to harness the energy from renewable technologies (Bellos, Tzivanidis et al. 2017). The share of various energy sources in the total energy mix of Pakistan by the year 2021 for hydral, Regasified Liquefied Natural Gas (RLNG), Residual Fuel Oil (RFO), coal, gas, nuclear, wind, solar, and bagasse was 26, 19.66, 16.84, 12.8, 12.15, 6.68, 3.31, 1.07, and 0.98% respectively. Non-renewable energy contributes around 61.45% of total electricity generation in Pakistan which causes hazardous greenhouse gases (GHG) and exhaust emissions (Energy 2021). Pakistan aims to increase the share of electricity produced from renewable sources (solar, wind, and biomass) to 30% by 2030 (Uddin, Shaikh et al. 2021). Wind power plants have low-capacity factor (CF), intermittency issues, and noise pollution. Whereas high costs, food shortage, reduced efficiency, and a large land requirement are associated with biomass. Solar energy is among the most promising renewable energy options for Pakistan, owing to abundant solar radiation in the Sun Belt region, land and water availability, and high output efficiency. The leading solar technologies deployed for power production are Photovoltaic cells (PV) and concentrating solar power (CSP). The primary technology used to harness solar energy is photovoltaics (PV) cell, but it has shorter life span and storage drawbacks during non-solar hours of the day. Despite the more commercialization of PV systems, CSP technologies have several advantages over PV system because of their higher thermal efficiency, higher CF, better hybrid capability with other fuels and storage system to meet base, intermediate and peak load at night time (Hirbodi, Enjavi-Arsanjani et al. 2020). According to International Energy Agency (IEA) report, the total installed capacity of CSP plants will reach 982 GW as it becomes more competitive technology for power production in carbon-constrained regions of the world by 2050 (International Energy Agency 2014). However, due to the high initial cost, the actual growth

of CSP is much slower than expected (Chen, Rao et al. 2018). CSP research and economic policies have been developed rapidly worldwide (Amadei, Allesina et al. 2013,page 5). The solar radiations received by major regions of Pakistan are between 4.45 and 5.83 kWh/m²/day, and these values are much higher than the global average solar radiations of 3.61 kWh/m²/day (Zeroual, Ankrim et al. 1995, Ullah, Rasul et al. 2013). CSP technologies use mirrors to concentrate sunlight from collectors (heliostats) to receiver tubes where this heat gets absorbed by heat transfer fluid (HTF) flowing inside the tube. As a result, the HTF temperature increases, and this heat is transferred to water via heat exchangers, where it is converted into steam. This steam then enters the turbine and generate electricity as a result of enthalpy drop of steam. CSP technologies consists of four main categories which include Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR), Solar Tower Power (STP) and Dish Sterling technology.

STP technology continues to grow compared to other technologies as this is thermodynamically more efficient than LFR and PTC due to the higher outlet temperature of the system (Ogunmodimu and Okoroigwe 2018,page 5). STP system configuration uses many heliostats that track the sunlight by two-axis movement. These tracking mirrors reflect the sunlight to the stationary receiver located on top of the tower, capturing and storing thermal energy by HTF. HTF then returns to the heat exchangers, where stored heat energy is transferred to water, converting it into high-pressure superheated steam to produce electric power. STP technology often accompanies a thermal storage system that accumulates the excess solar energy collected by solar field and is used to run the plant; at times, solar radiations are not present (Srilakshmi, Suresh et al. 2017,page 1-2). Several studies have been reported to optimize the performance of STP plants throughout the world. A new method proposed by Casati et al. (Casati, Casella et al. 2015) was implemented to design a 100 MW STP plant with optimal storage hours in the USA, and the storage capacity was varied from 1 to 20 h for SM 1.5 to 3.5. Results of that study reported that optimal storage capacity corresponding to SM of 1.5 and 3.5 was 3 h and 20 h, respectively.

Solar multiple (SM) is the ratio of maximum thermal energy received by HTF to the input power required for power block to operate at the design point, and it has a significant role in the economic performance of plant because around 50% of the investment of STP plant is dedicated for heliostat field (Kolb, Jones et al. 2007). A hybrid solar-coal plant was optimized to get optimal SM by Zhao et al. (Zhao, Hong et al. 2017), and they concluded that LCOE and payback period were reduced with the optimization of SM. Design point DNI is a particular value of DNI, received by the solar field that produces the rated electric power output and is strongly dependent on solar radiations of a specific location (Chen, Rao et al. 2018). Low design DNI may result in an oversized solar field, and hence large investment for heliostats and more unutilized energy. Whereases high deign DNI may result in the undersized solar field, and thus smaller capacity factor with poor utilization of invested capital (Desai, Kedare et al. 2014). In the SAM software design point DNI is recommended to be computed at 12 noon on the summer solstice (between June 20-22 for Northern Hemisphere).

Capacity factor is the ratio of average energy generation to the maximum energy that could be generated if the plant operates at its full capacity during the whole period. Higher CF can be achieved with the integration of the TES system at high SM (Izquierdo, Montanes et al. 2010). There is no significant progress made by Pakistan for power production through CSP, apart from a Memorandum of Understanding (MoU) that has been signed between Pakistan and Korea to install a 300 MW CSP plant (Anwar, Mahar et al. 2018). Neighboring countries of Pakistan that have similar infrastructure and meteorological data are making steady progress in deploying the CSP technologies, including India and Bangladesh (Tahir 2021). The estimated potential of CSP without parametric optimization in 591 districts of India using SAM was evaluated to be 2700 GW (Purohit and Purohit 2017).

There are very few studies regarding the feasibility of CSP technologies in Pakistan. A comparative study was carried out for the techno-economic performance of four CSP technologies at four locations in Pakistan. It was reported that a 50 MW STP plant with air-cooling is a promising option for power production in Quetta. This study lacked in parametric optimization (Soomro, Mengal et al. 2019). A recent study presented by Tahir et al. (Tahir 2021), comprehensively analyzed a 100 MW PTC plant for six potential sites of Pakistan using SAM and performed parametric optimization. The minimum LCOE values reported under the optimized configuration of 100 MW PTC plant for Quetta and Pishin were 15.3 ¢/kWh and 14.7 ¢/kWh, respectively. The parametric optimization of the STP plant has not been considered in previous studies for potential sites of Pakistan.

The aim of this study is to compare the techno-economic feasibility of optimized design of 50 MW STP plant with perspective of maximum capacity factor and minimum LCOE. Optimal sizing of the solar field is obtained through number of heliostats and tower design parameters at nine stations of Pakistan receiving more than 1600 kWh/m² average annual DNI value. A multi-objective optimization technique was deployed to obtain optimal values of SM and TES hours for each station, and with optimal SM and TES hours, two types of molten salts; Salt 1 (60% NaNO₃ and 40% KNO₃) and Salt 2 (46.5% LiF, 11.5% NaF and 42% KF) were analyzed and best salt is selected. Finally, the most and least suitable stations for the installation of STP plant in Pakistan are proposed.

2. Solar Radiation Data

The solar radiation data used in the present work was measured by ESMAP of the world bank at nine stations which include Khuzdar (KZD), Hyderabad (HYD), Quetta (QUT), Lahore (LHR), Multan (MUL), Karachi (KHI), Bahawalpur (BHL), Islamabad (ISB) and Peshawar (PEW). The data was measured from 1st November 2014 to 30th April 2017 for Bahawalpur, Islamabad, Multan, and Lahore; for Peshawar, Karachi, and Hyderabad from 1st May 2015 to 30th April 2017; for Quetta and Khuzdar from 1st October 2015 to 30th April 2017 (Tahir, Hafeez et al. 2021). Two systems were used to measure this data, Tier 1 system was deployed at Islamabad and Bahawalpur, equipped with Kipp and Zonen CHP1 Pyrheliometer to obtain Direct normal irradiance (DNI), and Kipp & Zonen CMP21 Pyranometer having CVF4 ventilation system to measure Diffused horizontal irradiance (DHI) and Global horizontal irradiance (GHI). Tier 2 system was at rest of the stations to measure DNI DHI and GHI, equipped with CSP Services Twin-Sensor Rotating Shadowband Irradiometer (RSI). To measure relative humidity (R_H) and ambient temperature (T), Campbell Scientific CS215 was used at Tier 1 and Tier 2 (Amjad, Asim et al. 2021). The details about sensors used in both systems, calibration of sensors, accuracy and uncertainty of sensors is presented in the Ref (Tahir, Hafeez et al. 2020). The method proposed by the Baseline Surface Radiation Network (BSRN) (Long and Dutton 2010) was used for measured data quality check. First quality check of measured data is done by physical possible limits to recognize any large error present, maximum and minimum values given as eq. 1a and eq. 1b respectively. G_e is distance between earth and sun in Astronomical units, and G_{sc} is the solar constant (1367 W/m²). The second quality check is carried out by extremely rare limits, maximum and minimum values are given as eq. 2b and eq. 2a respectively. Third quality check is applied taking the ratio of measured DHI and GHI; ratio is a function of solar zenith angle (θ_{sza}), the limits are represented in eq. 3a and eq. 3b. Moreover, since cosine error is a function of θ_{sza} and it is maximum at lower solar altitude, so solar radiations data having $\theta_{sza} > 85^{\circ}$ were not considered (Hafeez, Asim et al. 2021).

$GHI > -4 \text{ W/m}^2$		(eq. 1a)
$GHI < 1.5 \ (G_{sc}/G_{e}) \ (\cos \theta_{sza}^{1.2}) + 100$		(eq. 1b)
$GHI > -2 \text{ W/m}^2$		(eq. 2a)
$GHI < 1.2 \ (G_{sc}/G_{e}) \ (\cos \theta_{sza}^{1.2}) + 50$		(eq. 2b)
<i>DHI/ GHI</i> < 1.05	$\textit{GHI} > 50 \text{ W/m}^2, \theta_{sza} < 75^{o}$	(eq. 3a)
<i>DHI / GHI</i> < 1.1	$GHI > 50 \text{ W/m}^2, 75^\circ < \theta_{sza} < 93^\circ$	(eq. 3b)

3. Methodology

Techno-economic analysis was carried out for the performance evaluation of the solar tower power plant at nine stations in Pakistan under different weather conditions. A 50 MW capacity concentrated solar power plant (CSP) is very common in the world (Trabelsi, Chargui et al. 2016). Since Pakistan has no CSP plants, it would be necessary to install a 50 MW PTC plant to cover the country's base, intermediate and peak loads. An Excel spreadsheet containing user-entered costs was used to provide plant costing information. The analysis of the plant was done with a multi-objective optimization technique using System Advisory Model (SAM). SAM software is developed and provided by the National Renewable Energy Laboratory (NREL), operated by the Alliance for Sustainable Energy for the United States Department of Energy (DOE), and can predict hourly energy production for renewable energy projects (Blair, Dobos et al. 2014, Hernández, Barraza et al. 2020). Several scholars have used this simulation tool to assess the performance and financial feasibility of a variety of standalone and hybrid renewable energy technologies (Bai, Liu et al. 2017, Awan, Mouli et al. 2020, Nassar, Abdunnabi et al. 2021).

3.1. Economic and technical modelling

A comprehensive analysis of economic and technical parameters was conducted before the simulations. The main sources of economic parameters were accordingly taxing system of Pakistan and tariffs approved by the National Electric Power Regulatory Authority (NEPRA) for various PV power plants, including Quaid-e-Azam Solar Power, Zorlu Solar Pakistan and Javed Solar Park (Pvt.) Ltd. due to similarity in the taxing policies of PV and CSP for the same country (Authority 2021). Solar power tower technology with a single owner was considered. The exchange rate of 155.007 Rs per US \$ (as on March 19, 2021) was used for the analysis (Pound Sterling Live 2021). The costs of some technical components of the STP plant were used as recommended by SAM (National Renewable Energy Laboratory and Department of Energy 2020). These values are updated in each new version of SAM according to market trends. Project life period was taken as 25 years for all stations, comprising of 2 years for construction and 23 years for operational life. All the economic parameters were assumed the same for nine stations, as these stations are in the same country, ignoring small variations in financial factors for each station. All the main input cost parameters for the proposed plant with thermal storage and no backup system are summarized in Tab. 1.

Component	Cost	Component	Cost
Site improvement cost	16 US\$/m2	Total Land cost	2000 US\$/acre
Solar field	140 US\$/m2	EPC and owner cost	11% of direct cost
Thermal storage (Two tank)	22 US\$/kWh	Contingency	8 % of subtotal
Moratorium	5 years	Inflation rate	8 % /year
Insurance rate	0.5% of installed cost	Real discount rate	6.25 % /year
Net salvage value	10 % of installed cost	Total Land cost	2000 US\$/acre

Tab. 1: Summary of economic parameters

Design-point DNI values for each station were taken on the summer solstice at solar noon between June 20 to 22 for Northern Hemisphere to minimize energy losses for each station as recommended by SAM. The design point DNI values were evaluated to be 777, 858, 599, 633, 544, 450, 457, 503 and 640 W/m² for measured data of KZD, QUT, HYD, ISB, KHI, LHR, MUL, BHP and PEW stations respectively. The built-in capability of SAM, due to integration with NREL's SolarPILOT[™] software, was used to optimize the geometrical parameters of the heliostat field, which include receiver height, receiver diameter, tower height, heliostat count and field layout based on measured data of respective location, SM, and design point DNI. These parameters were optimized each time as the SM and design point DNI were changed. This standard optimized modelling of the solar field with two tank energy storage, air-cooled system, and steam Rankine cycle, as defined by NREL, were used for STP configuration. Two types of molten salts were used, designated as Salt 1 (60% NaNO₃ and 40% KNO₃) and Salt 2 (46.5% LiF, 11.5% NaF and 42% KF).

Parameter	Value	Parameter	Value
Material type	Stainless AISI 316	HTF hot temperature	574 °C
Boiler operating pressure	100 Bar	HTF cold temperature	290 °C
Storage type	2 Tank	Condenser type	Air-cooled
Tank height	12 m	Thermal power cycle	Rankine cycle
Cycle thermal efficiency	41.2 %	Annual degradation	0.4 % /year
Estimated gross to net conversion factor	0.9	HTF type	Molten salt

Tab. 2: Summary of technical parameters

3.2. Optimization procedure

The present study estimates maximum CF and minimum LCOE for plant having thermal storage and no backup system with different combinations of SM and TES hours for each station. To optimize output parameters (CF and LCOE) simultaneously, a multi-objective optimization approach was adopted to obtain optimal values of SM, TES hours, and heliostat field for each station (Awan, Mouli et al. 2020, page 8). After defining all technical and economic parameters, TES hours were varied from 4 to 16 h for SM from 2 to 3. The solar field was optimized for each new value of SM by running an optimization wizard tool. The optimized values of SM, TES, and heliostat field through plots for each station were listed in Tab.3 and Tab.4, respectively. A comparison was made, based on minimum LCOE and maximum CF, among nine stations by taking into account the optimized results. Further, two molten salts were also compared, and the best molten salt is

proposed. The structure adopted for the simulation study is presented in Fig. 1.



Fig. 1: Simulation procedure of 50 MWe STP plant

4. Results and Discussion

4.1. Optimal SM and TES hours for each station

The determination of optimal SM and TES hours are the key technical parameters for the techno-economic analysis of the STP plant to get a high value of CF and a low value of LCOE. Based on that, an optimized combination of SM and TES hours is chosen for every station based on two output parameters i.e., CF and LCOE. Optimized combinations are so obtained to give the highest CF and least LCOE for each station. It is observed that CF has a direct relationship with both SM and TES hours, as represented in Fig. 2(a), Fig. 3(a) & Fig. 4(a). This is because smaller solar field can use a little part of the solar resource available and hence plant can operate for small duration at its rated capacity during off-peak times, while the large solar field can absorb much of solar energy and the plant can operate for longer duration at its rated capacity during off-peak times. For a specific SM, CF increases linearly with an increase in TES hours at the start, and it becomes almost stable after a certain value of TES hours. This is because, with TES hours increasing, the capacity of the system to store thermal energy also increases. However, the large storage capacity of a system will result in higher thermal losses due to the large volume of the tank. Fig. 2(b), Fig. 3(b) & Fig. 4(b) reveals that LCOE decreases with an increase in TES hours for specific SM. Beyond a certain value of TES hours, LCOE breaks downtrend and tends to increase due to higher incremental cost for thermal storage compared to increment in annual energy generation (AEG). Furthermore, TES hours heavily depend on SM and design point DNI of a location. For a higher value of SM, TES hours and design DNI, the CF is high and LCOE are low. The two stations with the highest DNI are KZD and QUT, whereas the station with the lowest DNI is LHR among nine stations and is represented in Fig. 2, Fig. 3, and Fig. 4, respectively. From the plots of CF and LCOE, it is cleared that large TES capacity and SM are not always beneficial and need to be optimized for each station corresponding to maximum CF and minimum LCOE. For the KZD station, optimized results are obtained at SM 3 and TES 15 h and followed by QUT with profitable size of SM 2.9 and TES 14 h. From Fig. 4, it is observed that the maximum CF and minimum LCOE converges to SM 2.8 and TES 14h for LHR. Thus, there is a tradeoff between minimum LCOE and maximum CF to get the optimal values of SM and TES capacity. The same procedure is adopted for all stations, and final optimized results are listed in Tab. 3.



Fig. 2: Optimized output parameters of Khuzdar for different values of solar multiple against thermal energy storage hours (a) Capacity factor, (b) Levelized cost of electricity



Fig. 3: Optimized output parameters of Quetta for different values of solar multiple against thermal energy storage hours (a) Capacity factor, (b) Levelized cost of electricity



Fig. 4: Optimized output parameters of Lahore for different values of solar multiple against thermal energy storage hours (a) Capacity factor, (b) Levelized cost of electricity

Tab. 3: Optimal SM and TES hours for each station

Station	QUT	HYD	PEW	MUL	LHR	ISB	KHI	KZD	BHL
Solar Multiple	2.9	2.9	3	2.8	2.8	2.8	2.8	3	2.7
TES (hours)	14	15	14	13	14	13	14	15	13

4.2. Initial and optimized design model

The proposed plant was initially designed with the common values of SM 2 and TES 6 h taken from Tahir et al. study (Tahir 2021), while other cost and technical parameters are given in Tab. 1 & Tab. 2 respectively. The optimization of heliostat field can significantly enhance the performance of STP plant for a location. Small SM in STP plant is not capable of taking advantage of the available solar resource, while large SM requires extra land area, and their optical efficiency is low in the outer heliostat circles. There are some heliostats that do not contribute much during peak solar irradiance hours due to their defocused design to prevent exceeding the maximum thermal flux rating of the receiver. This signifies the need to determine the optimal value of a solar field that gives the plant optimal performance. Tower and receiver design are also important factors and are affected by blocking shading and attenuation losses. A large solar tower has a high construction cost and relatively high attenuation losses without any additional reduction in shading or blocking losses. It is evident that SM, tower height, and TES are interconnected (Carrizosa, Domínguez-Bravo et al. 2015). The performance of heliostat field and tower height is obtained through SAM. Fig. 5(a) and (b) shows the arrangement of heliostat field for KZD with initial and optimized design, respectively. The optimization process involves several iterations due to the interdependency of these parameters. Multi-objective optimization is used to optimize the sizing of these design parameters, and the comparison of the initial and optimized design model is represented in Tab. 4. The resulting receiver height, receiver diameter, tower height and heliostat count of optimized design are larger than that of the initial design for each station, due to higher SM and TES hours. A maximum and minimum value of design parameters are seen for LHR and QUT, respectively. It is found that sites with higher solar energy resources require low value design parameters, whereas sites with lower solar insolation need high-performance parameters.



Fig.5: Solar field layout for Khuzdar at (a) Initial design, (b) Optimized design

Station	Initial Design				Optimized design			
Code								
Design	Receiver	Receiver	Tower	Heliostat	Receiver	Receiver	Tower	Heliostat
narameters	height	diameter	Height	Count	height	diameter	Height	Count
parameters	(m)	(m)	(m)		(m)	(m)	(m)	
BHP	15.64	14.78	161.59	6343	17.95	16.66	178.95	8703
KZD	12.93	10.98	123.15	3974	15.87	12.82	145.38	5592
KHI	14.59	14.12	149.23	5897	17.54	16.86	180.95	8230
ISB	13.97	12.75	137.9	4966	16.50	12.22	168.92	6899
LHR	16.11	16.72	166.96	7249	18.49	19.11	192.40	10325
QUT	12.35	10.49	117.96	3631	14.99	13.34	145.38	5210
MUL	15.39	16.21	165.89	7138	18.24	19.03	191.20	10110
PEW	13.47	13.66	143.26	4830	16.09	17.27	169.57	7392
HYD	13.37	13.70	142.90	5270	16.92	17.20	178.08	7897

Table 4: Comparison of initial and optimized design

Fig. 6 depicts that AEG is more in the case of optimized design due to the larger solar field. It is observed that the maximum AEG of 318.40 GWh is for KZD, followed by 297.02 GWh for HYD and a minimum 208.9 GWh for PEW. For the KZD station, there are 5592 heliostats in the optimized STP plant, compared with 3974 in the initial design, resulted in 318.40 GWh of energy in the first year of operation. Although the optimized design has approximately 40% more heliostats than the initial design, but it also has approximately 70% more energy output. The same percentage increasing trend of heliostats and AEG can be seen for all the stations in Tab. 4 and Fig. 6 respectively. It is therefore required to optimize the design parameters for STP plant viability.



Fig. 6: Comparison of annual energy generation for initial and optimized design

4.3. Feasibility of STP plant

The optimized results are considered to the feasibility of the STP plant at nine stations. The CF, AEG, LCOE and NCC for each station at optimal design values of SM, full load TES hours, heliostat field and design-point DNI using Pakistan economic model with two salts are shown in Fig. 7 and Fig. 8. A comparison is made between two salts for nine stations based on CF is shown in Fig. 6(a), and it should be noted that all the stations with Salt 1 have higher CF as compared to the corresponding station with Salt 2. Considering the optimized results with Salt 1, the maximum CF of 80.8% is for KZD followed by HYD having CF of 77.2%, and the minimum CF is 53% for PEW. The highest AEG of 318.40 GWh is for KZD and the lowest AEG of 208.90 GWh for PEW with Salt 1 as shown in Fig. 7(b). It reflects that CF and AEG have the same trend for the respective station.

Fig. 8(a) represents a comparison between two salts for nine stations with the perspective of minimum LCOE, and it can be noted that all the stations with Salt 1 have lower LCOE as compared to corresponding stations with salt 2. With consideration of optimized results and salt 1, the minimum LCOE of 6.67 ¢/kWh is for KZD, followed by QUT having LCOE of 7.25 ¢/kWh, and from all stations, LCOE of 13.07 ¢/kWh is the maximum for LHR. Fig. 8(b) represents the NCC is almost same for salt 1 and 2. QUT has the smallest NCC of 441.31 M\$ due to good infrastructure, land, abundant solar radiations and water availability. KZD exhibits nearly 16% greater CF and AEG, and a reduction of 8.6% in the LCOE with Salt 1 compared to QUT.



Fig. 7: Comparison of output parameters for nine stations using two salts (a) Capacity factor, (b) Annual energy generation



Fig. 8: Comparison of output parameters for nine stations using two salts (a) Levelized cost of electricity, (b) Net capital cost

5. Conclusion

In this study, detailed analysis and optimization of SM, TES hours and solar field of a 50 MW STP plant with molten salt storage system, financial parameters in accordance with the taxing system of Pakistan, air-cooled and no backup, is carried out with the perspective of minimum LCOE, and maximum CF and AEG. For this purpose, initial design of STP plant for different climatic zones in Pakistan is proposed for SM 2 and TES 6h. Output performance parameters resulted in lower CF and higher LCOE value for each station despite of lower total installed cost of plant. The main reason for limiting value of output parameters is under-sizing of the plant and lower TES hours. The effect of SM and TES hours is analyzed to enhance the performance of output parameters of the designed plant. The comparison of initial and optimized design has shown that the performance of the STP plant was enhanced after parametric optimization. Furthermore, in the case of optimized design, the CF has increased by about 26.2, 24.5 and 18.2% for KZD, QUT and LHR, respectively as compared to the initial design. Also, LCOE has been lowered by an amount of 1.35, 1.50 and 2.21 ¢/kWh for KZD, QUT and LHR stations, respectively. Salt 1 is proposed as a best HTF for this STP configuration because of its better techno-economic performance. The most feasible location among nine stations for the STP plant with optimized SM, TES hours and solar field is KZD with the lowest LCOE of 6.67 ¢/kWh and highest CF of 80.8%, followed by QUT having LCOE of 7.25 ¢/kWh and CF of 69.5%. It is, therefore, concluded that KZD is most feasible, and LHR is not a suitable place for STP plant installation among nine stations due to its high LCOE of 13.07 ¢/kWh and low CF of 54% for Salt 1. The results of this study have revealed that optimization of solar field, SM and TES hours has a significant effect on the techno-economic performance of the STP plant.

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E-02. Hybrid Concepts

Techno-Economic Assessment of Hybrid PV And CST Systems

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Abstract

Detailed network analysis conducted on a comprehensive range of concentrated solar thermal (CST) plants with varying storage sizes for 48 sites in the Australian electricity networks has identified that the most viable option for CST at most locations uses a storage capacity of approximately 15 hours. Subsequently, a more detailed techno-economic study was conducted for several locations that were identified to be viable for CST implementation. A review of the engineering and site practicalities for these sites determined that the optimal plant size for technical and economic implementation was 125 MWe (net) with 15 hours of storage. In an extension to this assessment, this study aims to find the most cost-efficient hybrid CST and PV system that matches the performance of the optimized CST system at one site, Tom Price (Western Australia). This site has annual DNI of 7.50 kWh/m²/day, with the CST system having an annual generation of 983,120 MWh with the expected LCOE of 9.92 c/kWh. The assessment indicates that use of PV in hybrid systems can offer a more flexible design with potential benefits to land use and technical risk mitigation. Therefore, the criteria for selecting the type of systems and designing the power plant and the operational strategy should not only be based on the financial performance.

Keywords: Concentrated solar thermal, PV, hybridization, techno-economic analysis

1. Introduction

A detailed network analysis to determine the regions where CST technologies were likely to become viable in and the most relevant system designs determined a range of locations in different Australian networks where significant uptake was forecast based on projected future demand profiles and technology costs. All CST systems were based on a 100 MWe (net) power block size, but with varying storage capacities with corresponding field size changes. The preferred storage capacity was found to be either 12 or 15 hours, with the majority at 15 hours, for all sites identified potentially viable for CST operations (Beath et al., 2019). As a continuation in assessing opportunities for CST systems in the Australian electricity networks, technical and financial performance of eight different central receiver plant designs in twelve grid connected locations across Australia were investigated and optimum systems were identified. For each location, solar tower systems with the nominal capacity of 100 MWe (net) and thermal storage capacities from 6 to 18 hours were optimized. Findings of that study indicated that the optimum storage capacity was within the range of 14-16 hours (Meybodi and Beath, 2020), confirming the 15 hours was a suitable capacity.

A review of the central receiver power plants that were in operation, under construction or announced projects indicated that in practice the largest size of plants with a single tower was around 150 MW gross. There are technical challenges associated with larger size plants, with tower height being one of the limiting parameters. The tallest tower proposed is just over 260 m high (including the receiver). Therefore, it appeared that the largest practical size for a standard system to conduct techno-economic analyses of CST systems at different Australian locations was 125 MW net (almost 140 MW gross). This sizing also links to the storage capacity, with this system size allowing a storage of 15 hours. The expected output profile for the standard plant would be near-continuous full-load for the whole year, excepting periods of inclement weather and some reduction in winter due to lower solar availability. This study, by building on previous studies, provides an insight into the cost competitiveness of hybrid CST and PV systems in comparison with the previously optimized standard standalone CST system near Tom Price, WA (annual DNI =7.50 kWh/m²/day), which is within a zone with high potential CST uptake as identified by previously conducted network analysis. Three operational strategies (i.e. scenarios) are considered and the performances of the hybrid and standard CST systems are compared from a techno-economic point of view. Fig. 1 shows the location of Tom Price, which is within the North Western Interconnected System network.



Fig. 1: Location of the Tom Price site

2. Methodology

This study aims to find the most cost-efficient hybrid CST and PV system that matches the performance of the previously optimized standard CST system (i.e. 125 MWe (net) with 15 hours of thermal storage). To achieve this, both technical and financial performances are assessed. Three scenarios are considered. In the first scenario, CST supplements the generation of the PV system and when there is no PV generation (i.e. from late in the afternoon until the next morning) it operates solely to match the standard system's output. It is noteworthy that there is a constraint on the steam turbine's partial load for all scenarios. Working at loads below 30% is not allowed; if supplementing PV output requires operating at below 15% of the nominal capacity, the turbine shuts down. For the partial loads between 15-29%, turbine works at 30% of the nominal capacity. In the second scenario, CST commences shutting down as soon as PV starts generating with only an overlap during the late afternoon, where CST supplements the PV generation for the last 2 hours of PV operation. In the third scenario, CST load drops to 30% as soon as PV system starts generating electricity in the morning. In the late afternoon, for the last 2 hours of PV generation it supplies the difference between PV and standard CST generations only if the shortage is above 30% of the nominal power, otherwise it keeps working at 30% load.

With each scenario, the hybrid system is designed following this procedure: for a given PV capacity solar field, tower and, receiver of the CST component of the hybrid system, which has the same power block and storage system as the standard plant, are optimized considering different solar multiples to minimize the difference between the average monthly generations of the standard and the hybrid systems. Differences between the average monthly generations of the two systems, have to be lower than a certain limit for all months, i.e. lowest possible (5%, 7%, or in few cases 9%). The different hybrid systems are compared based on the actual annual generation and Levelized Cost of Energy (LCOE) values. The system that meets the performance criteria (i.e. matching the annual generation of the standard system as closely as possible) and has the lowest LCOE is selected as the best hybrid system for the scenario.

NREL's System Advisor Model (SAM, version 2018.11.11) was used to model and optimize both PV and CST components of the hybrid system. As noted in the two previously published studies conducted by the authors (Meybodi and Beath, 2016; Meybodi et al., 2017), a thorough analysis of the international as well as Australian studies led to a detailed capital cost and O&M cost breakdown of a molten salt central receiver base case plant

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(100 MWe with 4 hours of two-tank molten salt thermal storage). The cost values have been updated to reflect cost reductions in the CST technology in recent years. The previously developed cost model, which allows for estimating capital and O&M costs for other sizes of the system and provides a detailed system cost breakdown, has been used to estimate the costs of the standard system and is used to calculate the costs of CST component of the hybrid system. Table 1 lists the SAM costing data for the standard system. For the capital cost of the PV system, the value of \$1463/kW is used (Graham et al., 2019). The O&M cost of the PV system is assumed to be 1% of the capital cost.

Item	Value	Unit
Site improvements	20.1	\$/m ²
Heliostat field	140	\$/m ²
Balance of plant	277.3	\$/kWe
Storage	26.4	\$/kWh _{th}
Fixed tower cost	3,193,998	\$
Tower cost scaling exponent	0.0113	-
Receiver reference cost	61,507,728	\$
Receiver reference area	761.121	m ²
Receiver cost scaling exponent	0.7	-
Contingency	7	%
EPC and owner cost	10.3% of the direct capital cost	_
O&M cost	83.7	\$/kW-yr

Tab. 1: The standard system (125 MWe and 15 h of storage) SAM costing data

LCOE is defined by Equation (1), where CAPEX is the total capital cost (\$), OPEX is the operational and maintenance cost (\$/y), n is life of project (years), r is the discount rate, E is the produced electricity (kWh/y), t is the year of the project, and LCOE is in c/kWh. The discount rate is assumed to be 0.07. The project lifetime was considered to be 30 years, comprising of 3 years of construction and 27 years of operation.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_{t} + OPEX_{t}}{(1+r)^{t}}}{\sum_{t=1}^{n} \frac{E_{t}}{(1+r)^{t}}}$$
(eq.1)

3. Results and discussion

Table 2 provides the summary of results and Fig. 2 shows the average annual output profiles for the three scenarios at the studied site. It is noteworthy that the generation values for PV and CST components of the hybrid system are the net generated electricity by these systems that is supplied to the grid and excludes any surplus PV generation that would result in the system exceeding the nominal maximum system output. There is also provision in the model for PV output to be used internally to supply the parasitic loads of the CST system, which can result in complicated interpretations of the total system output compared to the sum of the individual CST and PV generation predictions. The hybrid system in the second scenario provides the best match to the standard CST system profile. This is due to that fact that in the first and third scenarios the hybrid CST system increases generation when the storage is filled early in the afternoon. However, selecting the operational strategy (the scenario) for a specific site may require considerations beyond the similarity in output profile to the standard system and instead be based on better economics (i.e. lowest LCOE, as achieved in the second scenario) or closest match to the actual annual generation (i.e. as achieved by the third scenario).

Scenario	First	Second	Third	Standard System
LCOE (c/kWh)	9.91	9.90	10.05	9.92
Annual generation (MWh)	1,026,199	1,051,524	993,878	983,120
Difference in generation with respect to the standalone system (%)	4.38	6.96	1.09	-

Tab. 2: Summary of results



Fig.2: Average annual output for different systems

3.1. Equipment cost comparison and sensitivity analysis

Fig. 3 shows the total equipment cost of the hybrid systems under the three scenarios as well as the standard CST system. The standard system has the lowest equipment cost and the second scenario is the most expensive option

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but has the lowest CST system cost. To clarify the cost conditions under which the hybrid systems are more cost efficient than the standard system, variations of the total equipment cost with changes in PV and CST solar field cost (including tower and receiver) have been depicted in Fig. 4. The power block and thermal storage are the same for all the systems and therefore have been omitted. Also, minor differences in the total land size and annual generation have been neglected due to the minimal impact on the assessment. Based on this simplification, the capital cost of the system components translates to being representative of the overall LCOE value.

The contour areas represent the total equipment cost of the hybrid system when the corresponding PV and heliostat field costs are used in the costing, with system costs changing between scenarios due to differences in the system designs. The slopes of the contours vary due to the differences in the relative contributions of PV and CST components to the cost of the total hybrid system equipment. The regions of the graph where the standard CST system is cheaper or more expensive than the hybrid system are indicated by color changes, with a diagonal transition line where the system costs are identical. This varies depending on the hybrid system considered, as the cost relative to the standard CST is affected by the different split between PV and CST components in the hybrid system design. This means that for every different way of optimizing a hybrid system there are different costing points that influence whether the standard CST or hybrid systems are the best economic decision. It is evident that the hybrid system design in the third scenario is the more likely to be cost effective compared to the standard CST system, will the hybrid design in the first scenario is least likely to be cost effective.



Fig. 3: Total equipment cost



Fig. 4: Impact of PV and CST field cost on the competitiveness of the hybrid system

4. Conclusion

This study considered the potential benefits of incorporating solar photovoltaic systems in hybrid combination with the concentrated solar thermal plants to produce hybrid plants with the same generation profile that has been projected to be desirable in the future electricity networks. A simplified description of the impact of hybridization on the plant design is that the daytime generation from photovoltaic panels will reduce the need for daytime generation from the solar thermal plant, so reduce the heliostat field, receiver, and tower sizes, but the storage system and power block will remain the same size in order to produce the required night-time production. The potential use of battery storage for photovoltaics was not included in this analysis.

As the study was conducted, it became apparent that different design and operational strategies for the hybrid system could achieve similar generation profiles to the CST-only system. Three alternative scenarios were considered for the design of the hybrid systems, all with different outcomes:

- Simple PV replacement of portion of the heliostat field used for daytime operations Power block was allowed to supplement the PV generation and ramp up when the storage fills, so very high output occurs in the afternoons in summer and may require shedding if the network connection is limited.
- PV for daytime operations, but with operational parameters limiting output of the combined hybrid system to accurately match the target output profile.
- Reduced PV implementation to minimize the intermittent operation of the power block This approach is intended to both reduce the likelihood of maintenance issues arising from excessive power block starts and to increase the reliability of the system during cloudy daytime operations.

5. Acknowledgments

The Australian Solar Thermal Research Institute (ASTRI) program is supported by the Australian Government, through the Australian Renewable Energy Agency (ARENA).

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Optical Design and Analysis of a Novel Spectral Beam Splitting Hybrid Photovoltaic and Concentrating Solar Thermal System

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Abstract

A simple and compact photovoltaic and concentrating solar thermal (PV/CST) hybrid system with a spectral beam splitting film is proposed in this study. The novel spectral beam splitting film is laid on a PV cell, which exhibits a superior spectral beam splitting, simultaneously achieving high average transmittance of 86.26% and reflectance of 54.03%. The Monte Carlo Ray-Trace Method (MCRT) is used to simulate the path of light and the concentrating characteristic between the primary reflect mirrors and absorber tube of the PV/CST hybrid system. The solar energy flux distribution on the surface of outer wall of the absorber tube is calculated via utilizing MCRT method. The photoelectric and photothermal characteristics of the PV and photothermal sub-unit are studyed with and without ITO SBS filter, respectively. The total energy of hybrid PV/CST system using ITO SBS filters was greater than a single PV unit by 33.3%, but decreased by 5.69% compared to individual photothermal units, with this system demonstrating considerable potential for application.

Keywords: Photovoltaic, concentrating solar thermal, spectral beam splitting film, solar energy flux distribution, Monte Carlo Ray-Trace Method

1. Introduction

Energy crisis is a global problem, owing to the increase in energy demand. In the current era, the depletion of traditional fossil energy and the severe environmental problems have promoted the vigorous development of renewable energy. Among them, clean, abundant and flexible solar energy has been vigorously promoted and applied by various countries (Zhou et al., 2020) Solar thermal and photovoltaic (PV) as chief technologies in the application of solar energy utilization. However, solar thermal utilization covers a large area and has low photothermal efficiency (Felsberger et al., 2021). The PV utilization has strong spectral selection properties (Cao et al., 2016). For meeting the requirement of maximized utilized solar energy, the photovoltaic and concentrating solar thermal (PV/CST) hybrid system with a spectral beam splitting (SBS) filter was proposed. The films achieve superior spectral beam splitting, which can transmit the wavelengths of sunlight that effectively produce electricity to the PV cells, but the unwanted wavelengths of sunlight for PV to the solar receiver for thermal energy (Zhang et al., 2021).

Most of the SBS filters mentioned in the above studies, including solid interference filter (Wang et al., 2020), liquid absorptive filter (Han et al., 2020), holographic filter (Ludman et al., 1992), luminescent filter (V and A, 2009), and spectrally selective solar cells (Widyolar et al., 2018), are frequently applied in hybrid PV/CST systems (Zhang et al., 2020). The Monte Carlo Ray-Trace Method (MCRT) as a statistical method of ray tracing, a large number of beams with radiation energy, after tracking the path of the beam, to achieve multiple lights stochastic processes such as reflection, transmission and absorption, statistically obtain the energy flow density distribution of the absorption surface (Qiu et al., 2015). MCRT method are widely used in solar thermal power systems to obtain the energy flow density distribution of the collector (Zhao et al., 2015). For instance, parabolic

trough collector (Cheng et al., 2012), linear Fresnel collector (Ma et al., 2017), dish collector (Hiba et al., 2019), and tower collector (Walzel et al., 1977), etc. However there are few reports on solar energy flux distribution in hybrid PV/CST system with SBS films by adopting MCRT method.

In this paper, the optical model of the PV/CST hybrid system was established in a TracePro software, including PV cells, the SBS filters, and absorber tube. Three-dimensional physical model of the PV cells with the SBS filters are designed to resemble the primary mirror field of the linear Fresnel reflector concentrator. The MCRT simulates the light concentrating characteristics of the absorber tube, and the energy flux distribution of the absorber tube are obtained. Simultaneously, analyzing the concentrating characteristic with and without ITO SBS filters in the PV/CST hybrid system.

2. Physical model

2.1. Optical filter

The optical filters exhibited prominent SBS characteristics with a high average transmittance in the wavelength range of 380–1100 nm and reflectance in the wavelength ranges of 300–380 and 1100–2500 nm, respectively. For improving the experiment efficiency, the simulation was employed to optimize deposition parameters. The design of the optical filter is carried out by using the TFCalc software, which based on the Needle optimization method (Tikhonravov et al., 1996). Considering the outstanding SBS effect and the simple production process, the ITO film was chosen and designed as SBS film. Fig. 1(a) illustrates the transmittance and reflectance spectral with different thickness of ITO films in TFCalc software. It can be seen that with the thickness increased, the transmittance curve moves toward the smaller value and the curve shape changes. Moreover, the whole reflectance spectral moves toward the long wavelength direction and the greater value. However, the actual experimental details can not be obtained through simulations.

The optical filters were prepared on low-iron glass by magnetron sputtering, which were put PV cells. The substrate of low-iron glass has the selective transmittance of light, making the transmittance of middle-infrared (MIR) and infrared (IR) regions of the solar spectrum is low and the visible and near-infrared (NIR) regions is contrary, thus realizing the initial SBS of the infrared spectrum range. The available energy of 380–1100 nm of the solar spectrum in total solar radiation energy is about 65%; the rest of 250–380 nm and 1100–2500 nm is not more than 15% and 20%, respectively. PV systems have strong spectrum selection characteristics, which generates electricity in the wavelength range of 400–1100 nm. The photoelectric characteristics of Si solar cells are observed with the external quantum efficiency (EQE), which indicates the response at wavelengths of 400 to 1100 nm, as illustrated in Fig. 1(b). The EQE of Si solar cell is equal to the ratio of the number of the wavelength-dependent photogenerated carriers or holes contributing to photocurrent to that of incident photons, which can reflect the real photoelectric conversion (PEC) capability of Si solar cell.

Therefore, the solar radiant energy of visible and NIR regions is the focus of our subsequent research. The optical SBS filters of ITO were prepared on glass by magnetron sputtering, which exhibits superior optical performance. The reflectance (ρ) and transmittance (τ) were measured using a Cary 7000 UV/Vis/NIR spectrophotometer. The ITO SBS film is expected to broaden the applications of PV/CST hybrid systems.

The reflectance (ρ) and transmittance (τ) were measured, by Eqs. (1) and (2).

$$\rho = \frac{\int_{0.3\,\mu m}^{0.38\,\mu m} \rho(\theta,\lambda)I_s(\lambda)d\lambda + \int_{1.1\,\mu m}^{2.5\,\mu m} \rho(\theta,\lambda)I_s(\lambda)d\lambda}{\int_{0.3\,\mu m}^{0.38\,\mu m} I_s(\lambda)d\lambda + \int_{1.1\,\mu m}^{2.5\,\mu m} I_s(\lambda)d\lambda} \qquad (eq. 1)$$
$$\tau = \frac{\int_{0.38\,\mu m}^{1.1\,\mu m} \tau(\theta,\lambda)I_s(\lambda)d\lambda}{\int_{0.3\,\mu m}^{1.1\,\mu m} I_s(\lambda)d\lambda} \qquad (eq. 2)$$

where λ , $\rho(\theta, \lambda)$, $\tau(\theta, \lambda)$, $I_s(\lambda)$ are the wavelength, reflectance at a certain wavelength, transmittance at a certain wavelength, and direct normal solar irradiance, respectively, as defined according to ISO standard 9845-1, normal radiance, air mass 1.5. The ρ and τ are equally weighted fractions.



Fig. 1 (a) The simulated spectrum of the different thickness ITO optical filter, (b) the EQE spectra of Si solar cell

2.2. CPC model

The photovoltaic and concentrating solar thermal hybrid system has been designed to use secondary concentrator to increase the energy flux density and make the energy flux distribution uniformly distributed on the receiver tube surface, avoiding generating local flux spots and thus increasing the optical efficiency. The compound parabolic concentrator (CPC) is crucial for the development of hybrid PV/CST systems. As a mature solar heat gathering device, CPC is very popular in concentrating solar systems.

The CPC is a non-imaging concentrator and without tracking of the sun, which includes an involute segment and parabola segment, the curves of the CPC is illustrated in Fig. 2. The theoretical model of CPC was designed by adjusting half-acceptance angle θ_{max} , absorber tube of radius r_1 , and glass tube of radius r_2 . The coordinates of the CPC curve are given by Eq. (3). The CPC collector is designed, which achieves the ray coming into the CPC aperture at an angle smaller than θ_{max} reaches the receiver; otherwise, the ray will return.

$$\begin{cases} x = r_1 \sin\theta - \rho \cos\theta \\ y = -r_1 \cos\theta - \rho \sin\theta \end{cases} \quad (eq. 3)$$

where

$$\rho = r_1(\theta + \beta)$$
 for $\arccos({}^{\Gamma_1}/{r_2}) \le \theta \le \pi/2 + \theta_{max}$

and

$$\rho = \frac{r_1[\theta + \theta_{max} + \pi_{/2} + 2\beta - \cos(\theta - \theta_{max})]}{1 + \sin(\theta - \theta_{max})} \text{ for } \pi_{/2} + \theta_{max} \le \theta \le \frac{3\pi_{/2}}{2} - \theta_{max}$$

then
$$\beta = \sqrt{\binom{r_2}{r_1}^2 - 1 - \arccos(\frac{r_1}{r_2})^2}$$



Fig. 2 schematic of CPC

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Meanwhile, the design of gap losses and truncation ratio of the CPC will be discussed. The glass tube exists a vacuum environment, which can reduce the heat losses by reducing heat conduction and convection. The gap between the absorber and the CPC reflector is required. However, the gap reduces the rays arrived to CPC and increases the reflection loss of the sun light. The complete CPC has a large reflection plate, but the concentration effect of upper reflection plate is poor. Therefore, an appropriate truncation ratio can reduce material of the reflector.

2.3. System optical model

The linear Fresnel reflector system is an essential precondition for the energy analysis, performance optimization, structure optimization, and operation control of hybrid PV/CST systems. Therefore, the hybrid PV/CST system utilizing SBS filter is improved base on the linear Fresnel reflector system, which consists of a primary mirror field (solar cell and SBS film), a CPC secondary concentrator, and an absorber tube, the schematic diagram of the hybrid PV/CST is shown in Fig. 3. The primary reflector of a tandem structure with an optical filter putting on PV cell, which is supported by a structure made of mild steel or aluminum. The solar radiation is distinguished by SBS film, selecting the solar spectrum regions with high photoelectric conversion rate (in the wavelength range of 400–1100 nm), and transmitting to the surface of the battery for photovoltaic utilization; the rest of the solar radiation is reflected to the absorber tube for photothermal usage (in the wavelength range of 1100–2500 nm).



Fig. 3 Hybrid PV/CST system diagram based on the spectral beam splitting film

The geometrical structure of primary mirror field is designed using Tracepro software and Matlab software, which is based on the MCRT Method. Fig. 4 shows the diagram of the Geometrical model of the hybrid PV/CST system, including PV cells, the SBS films, CPC, and absorber tube. The SBS film and CPC still needs to be continuously designed and optimized. The optical parameters of the primary reflectors and absorber tube are listed in Table 1.



Fig. 4: Geometrical model of the PV/CST hybrid system

Component	Item	Value
Single PV cell	width	160 mm
	length	400 mm
	interval	90 mm
Absorber tube	diameter	23.5 mm
	length	400 mm
	thickness	2 mm
	focus	1500 mm
	absorbance	0.95
Glass tube	diameter	29 mm
	length	400 mm
	thickness	3 mm
	transmittance	0.95

Tab. 1: Optical parameters of the PV/CST hybrid system

After a simple analysis of original and additional ITO SBS film PV Cells by the I-V curve, the energy of the hybrid PV/CST system were theoretically analyzed from the perspective of the law of conservation of energy. The energy obtained by PV cells (E_{PV}) and absorber tube ($E_{absorber}$) without SBS filters can be calculated by Eqs. (5) and (6):

$$E_{PV} = \int_{0.3 \,\mu m}^{1.1 \,\mu m} \tau(\theta, \lambda) I_{s}(\lambda) d\lambda \quad (eq. 5)$$

 $E_{absorber} = \int_{0.3\,\mu m}^{2.5\,\mu m} \rho(\theta,\lambda)_{mirror} \alpha(\theta,\lambda) I_s(\lambda) d\lambda \quad (eq.~6)$

where $\rho(\theta, \lambda)_{\text{mirror}}$ and $\alpha(\theta, \lambda)$ are the reflectance of the primary reflect mirrors at a certain wavelength and absorptance of the absorber tube at a certain wavelength.

The energy obtained by PV cells (E_{PV}) and absorber tube ($E_{absorber}$) with a 135 nm-thick ITO SBS filters can be calculated by Eqs. (7) and (8):

$$\begin{split} E_{PV,SBS} &= \int_{0.3 \ \mu m}^{1.1 \ \mu m} \tau(\theta, \lambda)_{SBS} I_{s}(\lambda) d\lambda \quad (eq. \ 7) \\ E_{absorber,SBS} &= \int_{1.1 \ \mu m}^{2.5 \ \mu m} \rho(\theta, \lambda)_{SBS} \alpha(\theta, \lambda) I_{s}(\lambda) d\lambda \quad (eq. \ 8) \end{split}$$

where $\tau(\theta, \lambda)_{SBS}$ and $\rho(\theta, \lambda)_{SBS}$ are the transmittance and reflectance of the ITO SBS filter at a certain wavelength; $\alpha(\theta, \lambda)_{SBS}$ is the absorptance of the absorber tube at a certain wavelength.

3. Results and discussion

3.1. Optical filter

The SBS performance of the ITO SBS film is shown in Fig. 5(a), which has superior spectral beam splitting. From the figure, the spectrums vary with the thickness of the ITO SBS film. After simulations of the TFCalc software, we selected two samples with a thickness of 135 nm and 185 nm for subsequent experiments, indicated by the red curve and the black curve in Fig. 5(a), respectively. From the figure, we can see that the ITO SBS film are more selective than the glass for the transmitted and reflected spectra. It is clear that increasing the thickness of the ITO SBS film increases the reflectance in the wavelength range of 1100–2500 nm and reduces the transmittance in full spectral wavelength range. The ITO SBS film with a thickness of 135 nm has a average transmittance of 86.26% in the region of 380-1100 nm and reflectance of 54.03% in the rest region of the solar energy spectrum (300-2500 nm). And the ITO SBS film with a thickness of 185 nm has a average transmittance of 78.42% in the region of 380-1100 nm and reflectance of 43.39% in the rest region of the solar energy spectrum. Due to PV solar cells have strong spectrum selection characteristics in the region of 380-1100 nm, we placed the ITO SBS films to PV solar cells for achieving spectrum splitting. The current-

voltage (I-V) and power-voltage (P-V) curve of a PV cell at a total solar irradiance intensity of 1000 W/m2 (1 sun) has the shape shown in Fig. 5(b). Moreover, PV cell performance parameters are usually measured by standard test conditions (STC) at a temperature of 25°C and coefficient of air mass (AM) of 1.5. Thereinto, the intersection between the I-V curve and x as well as y axis are open-circuit voltage and short-circuit current, respectively. Based on the I-V curve, we can calculate the power produced by the PV cell via the equation P=IV. The I-V curve for a PV cell shows that the current is essentially constant over a range of output voltages, when the total solar irradiance intensity is maintained constant. After adding the ITO SBS film, the short-circuit output current and maximum power of PV cells were decrease due to spectral changes on the surface of the photovoltaic cell. The detailed electrical performance characteristics of original and additional ITO SBS film PV Cells are listed in Tab. 2. The results demonstrate that the original PV cell system achieves the short-circuit current (I_{se}) of 0.139 A, along with the open-circuit voltage (V_{oc}) of 0.59 V, the maximum Power (P_{MAX}) of 0.058 W, the fill factor (FF) of 0.70, and the photoelectric conversion efficiency (PCE, η) of 14.39%. The PCE was measured by Eq. (4). The ITO SBS film acts as a spectrum splitter, which can transmit the sunlight of wavelength range of 380–1100 nm. The PCE of PV cell were 11.71% and 12.54% when ITO SBS films of 185 nm and 135 nm stack on the PV cells, respectively.

$$\eta = FF \times \frac{I_{SC} \times V_{OC}}{q_{PV} \times A} \times 100\% \quad (eq. 4)$$

where q_{PV} is the solar radiation intensity received on the surface of PV cell, and A is the PV cell area.



Fig. 5 (a) The transmittance and reflectance spectra of the glass and ITO SBS film, (b) I-V Curve of PV Cell and ITO SBS film

	Isc (A)	V _{oc} (V)	$P_{MP}(W)$	I _{MP} (A)	V _{MP} (V)	FF	η (%)
original	0.139	0.59	0.058	0.125	0.46	0.70	14.39
ITO-185 nm	0.112	0.59	0.047	0.102	0.46	0.71	11.71
ITO-135 nm	0.120	0.59	0.050	0.109	0.46	0.71	12.54

Tab. 2: The electrical performance characteristics of original and additional ITO SBS film PV Cells

3.2. CPC model

The shape of the CPC varies with the θ max. The larger the CPC θ max, the smaller its maximum opening width and the shorter its reflector plate. That is, the shape of the larger the θ max is more "round" of the CPC. Fig. 6 shows the path light rays diagram increasing the θ max from 20° to 35°.

When the CPC is used in combination with the linear Fresnel reflector system, the light is reflected by the primary reflect mirror cannot all enter the opening of the CPC due to the original CPC reflector blocks a portion of the reflect light. Therefore, part of the CPC reflector blocks needs to be truncated. The ratio of the distance between the CPC opening and the center line of the collector tube and the original reflector plate length of the CPC is called the truncation ratio. The shape of the CPC varies with the truncation ratio, the smaller the length compared to the original CPC reflection plate. Fig. 7 shows the path light rays diagram with different truncation

ratios of CPC. It can be seen that to ensure the uniform distribution of the energy flow density on the absorber tube, the truncation ratio needs to select an appropriate value. Meanwhile, the opening width of CPC is large enough to make all the reflected light of the primary reflect mirror field can enter the CPC and directly reach the surface of the absorber tube. Overall, the proper truncation ratio of the CPC can allow more light into the CPC while greatly reducing the amount of CPC materials and reducing the cost.



Fig. 6: The path light rays for CPC of different θ_{max} (a)20°, (b)25°, (c)30°, and (d)35°



Fig. 7: The path light rays for CPC of different truncation ratios (a)0.9, (b)0.8, (c)0.4, and (d)0.3

3.3. System optical model

Fig. 8 (a) presents the path light rays of the linear Fresnel reflector system, which has a plate at focus position to observe the spot size form the primary reflect mirrors. The analysis of the spots of the primary reflect mirrors found that the light reaches the focus of 1500 mm high with the spot size of about 100 mm, as shown in Fig. 8(b). Therefore, the CPC is designed to ensure that its opening is wide so that all the reflected light has access to the CPC.

After multiple simulation of CPC with different 0max and truncation ratio in Matlab to Tracepro software. The

optimized θ max and truncation ratio of the CPC are 30° and 0.3, respectively. The obtained light path diagram of the linear Fresnel reflector system, as shown in Fig. 9(a). Fig. 9(b) show the map of the circle energy flow density distribution on the surface of the absorber tube with and without ITO SBS filter, which are symmetrical and non–uniformity. As illustrated in this figure, the curvilinear trend of the circle energy flow density distribution with and without ITO SBS filter are significantly consistent; only the values are different. In conclusion, the ITO SBS filters reduce the obtained energy from a single PV system and a single photothermal system.



Fig. 8: (a)The path light rays of the linear Fresnel reflector system with a plate, (b) Schematic representation of the spot size of the reflected light at 1500 mm



Fig. 9: (a)The path light rays of the linear Fresnel reflector system with a CPC, (b) Solar energy flux distributions on absorber tube The quantitative analysis finds that the energy calculationes are conducted to evaluate the role of the ITO SBS filter of the hybrid PV/CST system. After the addition of the ITO SBS filters, the PV efficiency was reduced by 3.47%, and the photothermal efficiency was decreased by 26.02%. However, the total energy of PV and photothermal using ITO SBS filters was greater than a single PV unit by 33.3%, but decreased by 5.69% compared to individual photothermal units. It could be concluded that adding the ITO SBS filter was promising in hybrid PV/CST system.

4. Conclusion

The PV/CST hybrid system with a novel ITO SBS filter is developed based on the linear Fresnel solar thermal technology. The ITO SBS filter divides the spectrum into two parts, which has high transmittance of 86.26% in

the wavelength range of 300–1100 nm and high reflectance of 54.03% in the wavelength range of 1100–2500 nm. The hybrid PV/CST system utilise the full spectrum sunlight, which exploits transmitted sunlight to PV utilization and reflected sunlight to photothermal utilization, respectively. By using the I-V curve and MCRT method, photoelectric and photothermal characteristics were studyed. The photoelectricity conversion efficiency and energy analsys were theoretically calculated. The results indicate that the PCE of PV cell decrease by 12.9% when ITO SBS films of 135 nm stack on the PV cells; the total energy of hybrid PV/CST system using a 135 nm-thick ITO SBS filters was greater than a single PV unit by 33.3%, but decreased by 5.69% compared to individual photothermal units. Moreover, the curvilinear trend of the circle energy flow density distribution with and without ITO SBS filter are significantly consistent. It is concluded that the hybrid PV/CST system with ITO SBS system has enormous potentialities, and it still needs time and vitality to develop in the future.

5. Acknowledgments

This work was funded by the National Key R&D Program of China (No. 2019YFE0102000).

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E-04. Solar Receivers and Heat Transfer Media

Triethylenglycol as Novel Heat Transfer Fluid for CPVT Collectors with Spectral Splitting

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Abstract

Concentrating PVT (CPVT) collectors using the approach of Spectral Splitting are designed to provide thermal energy at high temperature level and electricity simultaneously with optimised efficiency. Among others, the Spectral Splitting effect can be achieved by a combination of a solid and a liquid absorption filter. In such a case, the utilised liquid serves both as optical filter and as heat transfer fluid and needs to fulfil several optical and thermodynamic requirements. Triethylenglycol (TEG) was investigated as a potential candidate fluid for utilisation in a Spectral Splitting CPVT receiver with a desired output temperature of 200°C. The performed analysis involves the mathematical description of temperature-dependent fluid properties, thermal expansion measurement, long-term thermal stress, and UV exposure tests. The main parameters for monitoring possible impacts of the stress tests are the spectral and the weighted transmittance values of the fluid, as these are essential properties for a stable long-term operation of the considered CPVT collector including Spectral Splitting. The investigation of TEG confirmed its suitability for the described application. The characteristic of the spectral transmittance in initial state shows the required downwards step at a wavelength of 1100 nm that is essentially necessary for the combination with a solid filter in the Spectral Splitting configuration. The UV exposure with a dosage of 50 kWh/m² has negligible effect on the optical fluid properties. The long-term thermal stress tests caused an acceptable decrease in weighted transmittance of -3.2 percentage points within the spectral band from 780 nm to 1100 nm.

Keywords: Heat transfer fluid, Spectral Splitting, transmittance, temperature stress, UV exposure

1. Introduction

Solar energy reveals rapidly increasing relevance for tackling the central challenge of the century, the transition of the global energy supply towards emission-free solutions (REN21, 2020). Besides the established technologies of photovoltaics (PV) and solar thermal energy conversion (T), the combination of both as hybrid or PVT systems can have several advantages in terms of efficient area utilisation, reduction of installation costs or increase of electrical energy yield (Zenhäusern, 2017). If industrial energy demand with higher temperature requirements shall be supported by PVT, concentrating systems (CPVT) have to be considered. However, CPVT collectors have to deal with the challenge to prevent an overheating of the PV cells in order to ensure acceptable electrical energy conversion efficiency, while providing output temperatures as high as possible. The concept of "Spectral Splitting" appears to be a promising approach to overcome the described discrepancy (Imenes and Mills, 2004). Thereby, the full spectrum of the incident concentrated solar irradiance is split into several segments by selective reflection or absorption. The PV cells only receive the specific spectrum segment where the electrical energy conversion works with highest efficiency, whereas all other wavelength ranges of the spectrum are directly converted into heat within the thermal receiver part. In this way, the waste heat dissipation inside the PV cells and hence the cell temperature can be reduced, resulting in a significant increase of electrical conversion efficiency.

Various constructions of Spectral Splitting CPVT receivers have been developed over the last decades (Daneshazarian et al., 2018; George et al., 2019; Imenes and Mills, 2004; Mojiri et al., 2013). Heading towards experimentally viable solutions, compact receiver designs combining solid and liquid beam splitting appear to be highly suitable for implementation and possible subsequent product development, because their constructions are rather simple, and the solid absorption filter with selectable optical characteristics provides a certain adjustability of the ratio between electrical and thermal output (Huang et al., 2021). The fluid applied for such receiver constructions serves two different purposes. On the one hand, it works as the heat transfer fluid (HTF), extracting the heat absorbed by the solid filter and transferring it to the respective heat sink. On the other hand, the fluid is an important part of the Spectral Splitting concept, as it defines the upper threshold wavelength of the spectrum range provided to the PV

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cells. Pure water can be a potential fluid, but if operating temperatures beyond 100°C are targeted, pressurisation has to be applied in order to avoid phase changes. However, the considered receiver concepts are typically constructed with glass components, in some cases even using rectangular cross sections (Hangweirer et al., 2015), which are less resistant against high pressure. For this reason, other kinds of HTF apart from water with a boiling point above 100°C at nominal pressure are required for the considered utilisation in a Spectral Splitting receiver. Furthermore, the HTF is directly exposed to concentrated incident sunlight in this case, what might lead to degradation of the medium, depending on its specific type.

In order to examine the suitability of candidate fluids like Silicone oil, synthetic oils or glycols for the described Spectral Splitting application, Looser et al. (2014) performed a comprehensive investigation of 18 different liquids, also linked to previous work done by Everett et al. (2012). This study included initial optical transmittance measurements, long-term low temperature and high temperature exposure at 75°C resp. 150°C for a duration of 700 h, as well as UV light exposure for more than 500 h. Among all tested fluids, Propylene Glycol (PG) turned out to be best suitable in terms of spectral transmittance, temperature reliability and chemical stability at UV-exposure.

This significant research outcome of Looser et al. (2014) might have been the basis for subsequent experimental investigations and performance tests of Spectral Splitting receivers, e.g. published by Stanley et al. (2016), Mojiri et al. (2016) or Han et al. (2021), where PG was used as heat transfer fluid. However, the maximum output temperature experimentally reached so far with PG was reported with 120°C by Stanley et al. (2016). The long-term temperature test of Looser et al. (2014) was limited to 150°C, and the boiling point of PG under nominal pressure is specified with 187°C (Looser et al., 2014). If the output temperature of a CPVT collector using the described concept of Spectral Splitting shall be increased above 150°C, the durability of PG is not confirmed. Moreover, if the design output temperature is specified with 200°C, the utilisation of PG under nominal pressure is clearly not possible, as the boiling point would be exceeded.

Resch and Höller (2020) recently developed several new CPVT receiver designs including the Spectral Splitting approach of combining solid and liquid absorption filtering. Two main aims of this research work are the target output temperature of 200°C and the realisability as a prototype for performing experimental measurements. As the current state of knowledge described above did not provide an appropriate fluid that can fulfil the optical and physical requirements for the specified temperature limit and at nominal pressure, a screening of potential HTF with a boiling point above 200°C was conducted. Most promising as a novel candidate fluid for an application in the developed Spectral Splitting CPVT receiver design was found with Triethylenglycol (TEG) from the German supplier WITTIG Umweltchemie GmbH. The boiling point of TEG without pressurisation is between 280°C and 295°C, it has crystal clear appearance, it is non-toxic and readily soluble in water (WITTIG Umweltchemie GmbH, 2015a, 2015b). These similarities in chemical and physical properties of PG and TEG reinforced the assumption that TEG could provide suitability for Spectral Splitting applications comparable to PG but accompanied by a significantly higher boiling point. Nevertheless, to the best of the authors' knowledge, the utilisation of TEG for the considered application is not reported yet. Therefore, the aim of this paper is to investigate the suitability of Triethylenglycol as heat transfer fluid and as the liquid filter part of the Spectral Splitting concept in combination with a solid absorption filter for an operating temperature up to 200°C.

2. Methodology

The performed analysis consists of a thorough characterisation of the TEG in its initial state and provides the most important thermodynamic properties in dependence of temperature, both graphically and mathematically. The investigation of the long-term stability of TEG involves a high-temperature test at 210°C for a duration of 700 h, a temperature cycling test within the range of 45°C to 210°C and for 180 cycles, as well as a UV exposure test for a duration of 833 h. Transmittance measurements were done in intervals of 100 h to observe potential changes in the optical properties of the fluid due to the applied stress tests.

2.1 Thermodynamic and physical properties of Triethylenglycol

Knowledge of fundamental thermodynamic and physical properties of a fluid is essential for its utilisation in a hydraulic system. If TEG shall be used as heat transfer fluid in the considered CPVT collector system with a nominal temperature span between 20°C and 200°C, the temperature dependency of the fluid characteristics is an important information. The supplier of TEG provided the following properties as a function of temperature in the range between -10° C and $+160^{\circ}$ C (WITTIG Umweltchemie GmbH, 2015c):

- Density ρ in kg/dm³
- Specific heat capacity c_p in kJ/kg·K
- Heat conductivity λ in W/m·K
- Dynamic viscosity η in mPa·s

The supplier's property information is only given graphically, and the considered temperature range is limited to 160°C. If the TEG characteristics are required for modelling purposes, a mathematical description of the fluid properties and their temperature dependency is needed. For this reason, MATLAB was used to extract 12 to 14 data points per curve from the graphical description. Curve fitting functionalities of MATLAB were applied to those datasets for obtaining the temperature dependent specification of TEG as mathematical equations.

The density ρ and the specific heat capacity c_p are described by linear equations, whereas the dynamic viscosity η is approximated by an exponential function. The heat conductivity λ is constant over the considered temperature range. For modelling the heat transfer between a fluid and a solid surface, the Prandtl number Pr of the fluid is essentially required. Therefore, this additional parameter was calculated for TEG by using the following equation (von Böckh and Wetzel, 2009):

$$Pr = \frac{c_p \cdot \eta}{\lambda} \tag{eq. 1}$$

Subsequently, the temperature dependency of Pr is approximated by an exponential function.

2.2 Thermal expansion test

As the thermal expansion coefficient of TEG is not specified by the supplier, this parameter was gained experimentally. A graduated measuring glass with 100 ml content, made of borosilicate glass and standardised according to DIN EN ISO 4788, was filled with 50 ml TEG at 20°C. The measuring glass remained open to atmosphere and was heated up in steps of 20°C to a maximum temperature of 220°C, using a heating chamber MEMMERT UF160plus. The expanding volume could be directly observed at the scale of the measuring glass and is reported for each of the intermediate steady state temperatures. This experiment was carried out three times in the same way, and the results are averaged for each temperature. Therefore, reading errors can be minimised and a strong reliability of the experimental outcomes can be confirmed.

Mathematical description of the measurement datasets is done by approximating a quadratic polynomial, using the MATLAB curve fitting functionality.

2.3 Spectral transmittance measurement and weighted transmittance calculation

The fluid TEG is a significant part in combination with the solid absorption filter for realising the required Spectral Splitting effect. Therefore, the spectral transmittance τ_s of TEG at each specific wavelength of the entire solar spectrum is crucial. Transmittance measurement was done with the fluid in its initial state to confirm the suitability of TEG in terms of the optical filter requirements that are illustrated in Figure 1 for an ideal Spectral Splitting configuration. In this case, a perfect solid absorption filter (red dashed line) shows a step in its spectral transmittance from 0 % to 100 % at a wavelength of 780 nm, whereas an ideal fluid (blue dashed line) reveals a downwards step of τ_s from 100 % to 0 % at a wavelength of 1100 nm. This idealised arrangement of solid filter and fluid would provide a "spectral window" between 780 nm and 1100 nm, where the irradiance *E* is neither absorbed by the filter nor by the fluid but transmitted to the PV cells of the CPVT receiver. In all subsequent illustrations, this spectral window is summarised as "ideal filter". The spectral irradiance *E* corresponds to the AM1.5 direct and circumsolar spectrum published by NREL (n.d.).



Fig. 1: Spectral transmittance τ_s of ideal solid filter and ideal fluid for application in a Spectral Splitting configuration

Besides the initial measurement, the spectral transmittance of the fluid was monitored periodically during the longterm stress tests described subsequently, for the purpose of detecting any change in the optical properties of TEG that could have an impact on the filtering effect. The spectrophotometer used for the transmittance measurements is a JASCO V-570 with a nominal wavelength spectrum from 250 nm to 2500 nm. A quartz glass cuvette, type 6030-UV, with a content of 3.5 ml and an optical length of 10 mm was filled with the corresponding TEG samples and inserted into the measuring beam of the spectrophotometer.

Additional to τ_s that specifies the transmittance for each single wavelength of the spectrum, an examination of the solar-weighted transmittance τ_w is meaningful for quantifying expected transmittance changes of the fluid by an exact number for a certain spectrum range. Furthermore, τ_w is related to the spectral irradiance and is therefore considering the varying intensity of the incident wavelengths. The calculation of τ_w is done for three ranges of the spectrum, corresponding to the three sections in Figure 1 that are given by the ideal filter: τ_{w1} from 280 nm to 780 nm, τ_{w2} from 781 nm to 1100 nm and τ_{w3} from 1101 nm to 2000 nm. The solar-weighted transmittance τ_w is calculated by the following equation (Miller et al., 2013):

$$\tau_w = \frac{\int \tau_s(\lambda) \cdot E(\lambda) \, d\lambda}{\int E(\lambda) \, d\lambda} \tag{eq. 2}$$

2.4 Long-term exposure to UV light

In contrast to conventional solar thermal collectors, the HTF of the designed CPVT collector with Spectral Splitting is directly impinged with concentrated sunlight, because it flows through glass tubes instead of opaque pipes made of steel or copper. The high-energetic UV part of the solar spectrum can harm the surface of various materials, e.g. plastics, and it can also change the optical property of a fluid, as it was already shown during previous research work (Everett et al., 2012; Looser et al., 2014). For this reason, a long-term UV exposure test was applied to the investigated TEG as well. The specification for this test bases on the standard *IEC62108 – Concentrator photovoltaic (CPV) modules and assemblies – Design qualification and type approval* (IEC, 2007), demanding a total UV dosage of 50 kWh/m² \pm 10 % for the spectrum range below 400 nm. A weathering test chamber ATLAS Ci4000 was used for this test. This chamber is equipped with xenon lamps that provide an irradiance of 60 W/m² in the broadband wavelength range between 300 nm and 400 nm. Hence, a test duration of 833 h was needed to reach the required accumulated UV dosage. Eight test tubes made of borosilicate glass with a content of 20 ml and an aluminum cap were filled with TEG in such a way that a small air bubble remained in the tube for compensating thermal expansion of the fluid, see Figure 2. The UV exposure test was started with all eight test tubes positioned in the weathering chamber. In intervals of 100 h respectively 133 h at the end of the procedure, one test tube was extracted from the chamber for measuring the transmittance of the fluid in the spectrophotometer.



Fig. 2: Test tube filled with TEG and remaining air bubble (foreground) and further test tubes prepared for long-term UV exposure test (background)

2.5 Long-term thermal stress by high-temperature exposure and temperature cycles

Besides the depicted stress of the HTF by exposure to UV light, the fluid must also withstand the claimed operating temperatures of the CPVT collector. Although the boiling point of TEG between 280°C and 295°C at nominal pressure promises principal suitability for operating the fluid at temperatures of 200°C and beyond, the impact of high temperature operation on the optical properties of TEG is unclear. Moreover, the investigations of Looser et al. (2014) on similar fluids like Propylene Glycol have already proven that high-temperature stress does influence the spectral transmittance and hence the filtering behaviour of such liquids. Therefore, conducting long-term thermal stress tests with TEG was essentially required to ascertain the applicability of the fluid for the described purpose. The investigation consisted of a high-temperature between $45^{\circ}C \pm 5^{\circ}C$ and $210^{\circ}C \pm 5^{\circ}C$ for 180 cycles with a cycle time of 4 h each. The heating chamber MEMMERT UF160plus was used for both tests. The fluid samples were stored in Erlenmeyer flasks made of borosilicate glass with a content of 250 ml and sealed with silicone plugs, supported by a spring mechanism that prevents the plugs from being lifted due to rising pressure within the flasks, see Figure 3.



Fig. 3: Erlenmeyer flasks filled with TEG and sealed with silicone plugs including safety mechanism, before starting the hightemperature test. Sample "L" contains air, sample "N₂" is passivated with Nitrogen.

Two flasks for each test were filled with 200 ml of TEG. The remaining volume in the first flask was filled with air, while in the second one the air was replaced by Nitrogen. These two kinds of gas volume inside the flasks were chosen to analyse the influence of potential oxidation on the optical properties of TEG, if the fluid is in direct contact with closed air. Every 100 h, the flasks were opened to extract 20 ml of fluid for performing transmittance measurements. The Nitrogen passivation was re-established after each fluid extraction process.

3. Results

3.1 Temperature dependency of thermodynamic and physical properties of TEG

The following graphical and mathematical specification of the temperature dependency of major fluid parameters may be helpful for the utilisation of TEG as a heat transfer fluid in the temperature range up to 200°C. Figure 4 condenses the temperature characteristics of density ρ , specific heat capacity c_p , dynamic viscosity η and Prandtl number Pr as graphical illustrations. The square marks are values taken from the supplier's data sheet, and the solid lines are fitted curves obtained by mathematical approximation. The Prandtl number Pr was not provided by the supplier but calculated from c_p , η and heat conductivity λ , see equation 1. Therefore, this curve does not contain any supporting points.



Fig. 4: Temperature dependency of major thermodynamic and physical properties of TEG: Density ρ in kg/dm³ (top left), specific heat capacity c_p in kJ/kg·K (top right), dynamic viscosity η in Pa·s (bottom left) and the Prandtl number *Pr* (bottom right)

The density ρ (in kg/dm³) of TEG is depicted in the top left quarter of Figure 4, showing a linear degression with rising fluid temperature. This characteristic is described by equation 3:

$$\rho(\vartheta) = 1.138 - 7.897 \cdot 10^{-4} \cdot \vartheta \tag{eq. 3}$$

By contrast, the specific heat capacity c_p (in kJ/kg·K) is increasing linearly with temperature, as illustrated in the top right quarter of Figure 4. Therefore, the mathematical approximation also reveals a linear equation as follows:

$$c_p(\vartheta) = 2.148 + 3.43 \cdot 10^{-3} \cdot \vartheta$$
 (eq. 4)

A significant temperature dependency of the dynamic viscosity η (in Pa·s) can be obviously observed in the bottom left quarter of Figure 4, given in logarithmic scale on the y-axis. η of TEG falls from 49.923 mPa·s at a temperature of 20°C down to 0.655 mPa·s at 200°C, corresponding to a factor of 76.2. The mathematical approximation yields an exponential function to describe the temperature dependent characteristic of η :

$$\eta(\vartheta) = 0.1386 \cdot e^{-0.06739 \cdot \vartheta} + 0.01954 \cdot e^{-0.01698 \cdot \vartheta}$$
(eq. 5)

The Prandtl number Pr (dimensionless) is directly proportional to the dynamic viscosity η . Therefore, its temperature dependency illustrated in the bottom right quarter of Figure 4 is also approximated by an exponential function:

$$Pr(\vartheta) = 1519 \cdot e^{-0.06577 \cdot \vartheta} + 214.4 \cdot e^{-0.01553 \cdot \vartheta}$$
(eq. 6)

The heat conductivity λ of TEG is constant in the temperature range from -10°C to +160°C, as specified by the supplier (WITTIG Umweltchemie GmbH, 2015c):

$$\lambda(\vartheta) = const = 0.196 \frac{W}{m \cdot K}$$
(eq. 7)

Correct implementation of the described equations 3 to 6 implies the corresponding temperature ϑ to be given in °C. Moreover, the validity of the approximations for the temperature range between 160°C and 200°C is neither confirmed by the supplier of the fluid nor by any experimental verification yet.

3.2 Thermal expansion measurement and mathematical approximation

The graphical result of the thermal expansion experiment with TEG is presented in Figure 5. The measured increase of volume with rising temperature is normalised to the base temperature of 20°C. The square marks indicate the measurement results, averaged for each temperature step, whereas the solid line represents the illustrated mathematical approximation. For the temperature range considered within the described application of operating a CPVT receiver, the fluid expands by approx. 15 % when it is heated up from 20°C to 200°C.



Fig. 5: Volumetric thermal expansion of TEG, normalised to base temperature 20°C

The mathematical description of the volumetric thermal expansion γ of TEG is provided by the quadratic polynomial in the following equation 8:

$$\gamma = \frac{V(\vartheta)}{V(20^{\circ}C)} = 0.9901 + 3.989 \cdot 10^{-3} \cdot \vartheta + 2.065 \cdot 10^{-6} \cdot \vartheta^2$$
(eq. 8)

The fluid temperature ϑ must be given in °C for obtaining the relative change of volume, related to the initial volume at the base temperature of 20°C.

3.3 Initial spectral and weighted transmittance values of TEG

Besides the investigated thermodynamic and physical properties of TEG, its optical behaviour is crucial for realising the targeted Spectral Splitting filter. The result of the spectral transmittance measurement of TEG in its initial state at delivery condition, before exposing it to any stress test, is presented in Figure 6, black solid line. This characteristic is compared to the spectral transmittance measurement of distilled water (blue dot-dashed line) and to the ideal filter behaviour (green dashed line). The spectral irradiance of the AM1.5 spectrum ASTM G-173-03 (NREL, n.d.) is inserted in grey.

The weighted transmittance τ_{w1} of TEG for the wavelength range between 280 nm and 780 nm is calculated by 93.4 %, and τ_{w2} between 781 nm and 1100 nm is 88.1 %. The spectrum range beyond 1100 nm should be absorbed

by the fluid, corresponding to low transmittance, but the calculation of τ_{w3} results in 33.0 %. This rather high value is caused by a local peak in the spectral transmittance that can be observed between 1200 nm and 1400 nm.



Fig. 6: Spectral transmittance measurement of TEG (initial state) and distilled water, in comparison with an ideal filter, referring to AM1.5 spectrum ASTM G-173-03 from NREL

3.4 Impact of long-term UV exposure on transmittance of TEG

The conducted exposure of eight TEG samples to an accumulated dosage of UV-light of 50 kWh/m² in the broad band between 300 nm and 400 nm results in only minor changes of the optical fluid properties. Figure 7 summarizes the spectral transmittance values τ_s for the reference sample "TEG initial" and the fluid samples extracted from the UV chamber in intervals of 100 h, respectively 133 h for the last one. Relevant changes of τ_s compared to the reference sample can be observed in the wavelength range below 400 nm, but no distinct trend with progressing test duration can be detected. In the spectrum range from 500 nm to 2000 nm, the spectral transmittance of all samples does not show noticeable deviation from the reference.



Fig. 7: Spectral transmittance measurements of TEG during UV exposure test in intervals of 100 h

Better quantification of the impact of the performed UV exposure test on the optical properties of TEG can be provided by comparing the weighted transmittance values τ_w before and after the measurement, separated for the three defined wavelength ranges, see Table 1. The absolute deviation of τ_w is between -0.5 percentage points (%P) and -1.2 %P, confirming that the UV exposure test with a dosage of 50 kWh/m² has negligible impact on the transmittance properties of TEG.

	τ _{w1} 280 nm – 780 nm	τ _{w2} 781 nm – 1100 nm	τ _{w3} 1101 nm – 2000 nm
TEG reference sample	93.4 %	88.1 %	33.0 %
TEG after 833 h UV exposure	92.2 %	87.5 %	32.5 %
Absolute deviation	-1.2 %P	-0.6 %P	-0.5 %P

Tab. 1: Changes of weighted transmittance τ_w of TEG after 833 h UV exposure test

3.5 Impact of long-term high-temperature test on transmittance of TEG

The results of exposing 200 ml of TEG to high-temperature of $210^{\circ}C \pm 5^{\circ}C$ for a duration of 700 h are revealed by Figure 8, showing the spectral transmittance τ_s for each extracted fluid sample in intervals of 100 h. The TEG was passivated with Nitrogen, which was refilled every time a sample was taken from the flask. The comparison to the reference curve "TEG initial" depicts a clear tendency of losing spectral transmittance in the spectral band below 780 nm with progressing test duration. By contrast, neither the wavelength range between 780 nm and 1100 nm, marked as "Ideal filter", nor the wavelengths beyond 1100 nm show major changes of τ_s .



Fig. 8: Spectral transmittance measurements of N2-passivated TEG during high-temperature test at +210°C in intervals of 100 h

These results are remarkably different if the TEG is not passivated by Nitrogen during the test. Figure 9 illustrates the spectral transmittance measurements of TEG samples from two different flasks that were tested simultaneously. In one flask, the remaining air volume was replaced by Nitrogen, while the other one was tested with air inside. Only the results of the test samples taken at 100 h, 400 h and 700 h are provided in Figure 9, both for the N₂-passivated TEG (red lines) and the air-filled flask (blue lines). Without passivation, the spectral transmittance τ_s of TEG decreases significantly after 700 h of high-temperature test, even in the spectral band between 780 nm and 1100 nm ("Ideal filter") that is important for the application of TEG in a Spectral Splitting CPVT receiver. Table 2 quantifies the impact of the performed high-temperature (HT) test by presenting the weighted transmittance values τ_w .

Tab. 2: Changes of weighted transmittance τ_w of TEG after	700 h high-temperature test for N2-passivated and air-	filled samples
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	$ au_{w1}$	$ au_{w2}$	$ au_{w3}$
	$280\ nm-780\ nm$	781 nm – 1100 nm	1101 nm - 2000 nm
TEG reference sample	93.4 %	88.1 %	33.0 %
TEG after 700 h HT-test, N2-passivated flask	72.6 %	86.7 %	32.7 %
Absolute deviation, N2-passivated flask	-20.3 %P	-1.4 %P	-0.3 %P
TEG after 700 h HT-test, air-filled flask	23.1 %	77.7 %	32.4 %
Absolute deviation, air-filled flask	-70.3 %P	-10.4 %P	-0.6 %P



Fig. 9: Spectral transmittance measurements of TEG during high-temperature test, comparing air-filled fluid sample with N₂passivated one

The results of the weighted transmittance values τ_w indicate that the performed high-temperature test has only minor impact on the optical performance of TEG in the wavelength band above 1100 nm. By contrast, in the relevant spectral band between 780 nm and 1100 nm, the decrease of τ_w is -10.4 %P for the air-filled flask, but only -1.4 %P for the N₂-passivated TEG sample. This effect of N₂-passivation becomes even more obvious in the spectral range below 780 nm, where the air-filled sample depicts a severe drop of τ_w by -70.3 %P.

3.6 Impact of long-term temperature cycling test on transmittance of TEG

The performed temperature cycling test between 45°C and 210°C fluid temperature for 180 cycles with a duration of 4 h each yielded the spectral transmittance results in Figure 10 for TEG passivated with Nitrogen. Again, samples of the fluid under test were extracted in intervals of 100 h for obtaining the corresponding spectral transmittance τ_s . The tendency with progressing test duration is comparable to the high-temperature test. A significant impact of this thermal stress on τ_s can be observed in the spectral range of short wavelengths below 780 nm, whereas the spectrum band above 1100 nm does not reveal any obvious change of τ_s . The relevant spectrum band between 780 nm and 1100 nm shows more degression of τ_s than it was observed during the high-temperature test.



Fig. 10: Spectral transmittance measurements of TEG during temperature cycling test (+45°C to +210°C) in intervals of 100 h

The described tendency in the changes of τ_s can be confirmed by the calculation results of the weighted transmittance τ_w , see Table 3. The spectral band between 280 nm and 780 nm shows a considerable reduction of τ_w by -49.6 %P, whereas the change of τ_w in the upper spectral range between 1100 nm and 2000 nm is negligible. The important spectrum band between 780 nm and 1100 nm only reveals a moderate decrease of τ_w by -3.2 %P.

	τ _{w1} 280 nm – 780 nm	τ _{w2} 781 nm – 1100 nm	τ _{w3} 1101 nm – 2000 nm
TEG reference sample	93.4 %	88.1 %	33.0 %
TEG after 180 temperature cycles	43.8 %	84.9 %	32.9 %
Absolute deviation	-49.6 %P	-3.2 %P	-0.1 %P

Tab. 3: Changes of weighter	l transmittance $ au_w$ of N ₂ -passivated	TEG after temperature cycling test
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4. Discussion and conclusions

The conducted investigation of Triethylenglycol revealed several findings that could be beneficial for its potential utilisation as heat transfer fluid in Spectral Splitting CPVT receivers.

The temperature dependency of the thermodynamic properties, density, specific heat capacity, dynamic viscosity and Prandtl-number are now available for TEG, both graphically and mathematically, for a temperature range up to 200°C. The derived approximation equations can be implemented in modelling approaches using TEG as heat transfer fluid. Especially the depicted characteristic of the dynamic viscosity η is important to consider, e.g. for engineering hydraulic systems with TEG, because it shows a significant decrease by a factor of 76 for a temperature rise from 20°C to 200°C. Furthermore, the thermal expansion of TEG is now described as a function of temperature. However, the mathematical description of the fluid parameters in the temperature range of 160°C to 200°C bases on an extrapolation of the supplier's data, without being confirmed experimentally so far.

The optical behaviour of TEG in its initial state is satisfying, because it shows high values of weighted transmittance for the wavelength range below 1100 nm, as well as the desired stepwise decrease of transmittance towards longer wavelengths. Although, the weighted transmittance in the spectrum range above 1100 nm is not as low as expected.

The long-term exposure to UV-light with a dosage of 50 kWh/m² has minor impact on the optical properties of TEG. The weighted transmittance only decreased by -0.5 %P to -1.2 %P over the entire spectrum range.

By contrast, thermal stress reduces the transmittance of TEG significantly, but only in the spectrum range below 780 nm. In the considered Spectral Splitting configuration, the short wavelengths < 780 nm are absorbed by the solid filter anyways. Therefore, a reduction of the fluid transmittance in this spectrum band is acceptable, because it does not influence the overall filtering performance. Temperature cycles cause more degradation of the fluid than long-term high-temperature exposure, but the reduction of the weighted transmittance by -3.2 %P for 780 nm to 1100 nm is reasonable. If TEG is not passivated by Nitrogen but in direct contact with air when thermally stressed, the decrease of weighted transmittance values is accelerated significantly. Therefore, it is not recommended to use TEG for operating temperatures of 200°C in hydraulic systems that are open to atmosphere.

Triethylenglycol appears to be a suitable heat transfer fluid for utilisation in CPVT collector applications. Especially, because it provides the right spectral transmission behaviour that is requested for realising the approach of Spectral Splitting. The boiling point of 280°C offers a wide range of applicability, and the low safety requirements ensure an easy handling. The reliability of TEG in terms of temperature stress and UV exposure is confirmed by the performed investigations.

5. Acknowledgments

This project is financed by research funds from the government of Upper Austria.

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E-06. Solar Fuels and Chemicals

Solar Hydrothermal Processing of Biomass: Influence of Temperature and Pressure on the Fuels

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Abstract

Before the extended use of fossil fuels, biomass was the main source of energy. Nowadays, there is an interest for its use in the production of different energetic materials, as well as added value substances. In order to obtain these products, biomass has to be transformed through different conversion process. Thermochemical biomass transformation presents an attractive option due to its ability to produce fuels quickly, along with the potential to decompose most biomass compounds, such as lignin. Hydrothermal processing (HTP) is a promising technology for being carried out at lower temperatures than pyrolysis and gasification and utilizing wet material up to 70% humidity content, saving biomass drying. However, one concern is that HTP typically uses fossil-generated electricity for heating. Therefore, to reduce its environmental impact, concentrated solar energy has been proposed as a heat source. In the present work, hydrothermal liquefaction of agave bagasse was performed in a solar furnace of 25kW. The experiments were carried out in a solar reactor specifically designed to work at maximum conditions of 220 bar and 500°C. The experiments were carried out with heating rate of 2°C/min. They considered different operational parameters of temperature (150, 250 and 300°C), initial pressure (10, 30 and 50 bar), residence time (0 and 60 min). The main results indicate that at lower temperatures of 250°C, a bio-oil with better energetic properties than that obtained by conventional pyrolysis at 450°C can be accomplished.

Keywords: Solar hydrothermal processing, solar thermochemical conversion of biomass, solar hydrothermal liquefaction.

1. Introduction

Thermochemical conversion processes are attractive alternatives for the biomass transformation due to their faculty to be performed in a short period of time (hours, minutes or even seconds), and the complete transformation of biomass compounds, for instance lignin. Thermochemical processes can be classified in three main routes: pyrolysis, gasification and hydrothermal processing (HTP) (Zhang et al., 2010). Nevertheless, the only one with the capability to be carried out with high moisture content biomass is the HTP (Guo et al., 2015).

One of the main drawbacks in HTP is the energy requirement to heat the process (Gasafi et al., 2008). According to previous studies (Giaconia et al., 2017), the use of a concentrating solar system to provide heat to a hydrothermal plant can reduce the energy demand of the process by 54%.

Xiao et al., 2019 performed an exergetic analysis of microalgae at hydrothermal processing conditions (160 °C and 20 bar) for anaerobic digestion and gas production. In this study, authors compared the exergy efficiency of biogas production by conventional hydrothermal processing technology and solar-driven hydrothermal treatment, the main results found that the exergy efficiency improves by around 5% by carrying out the solar-driven process

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(40.85%), in contrast with the conventional hydrothermal treatment (35.98%). This was attributed to the renewable solar energy that deleted the internal exergy loss, which results in improving methane production, compared to the conventional hydrothermal system. Although solar hydrothermal liquefaction of biomass is economically unattractive for its similarity in prices with conventional heating systems of hydrothermal liquefaction, solar hydrothermal processing presents higher thermal efficiencies. Giaconia et al., 2017 and Pearce et al., 2016 reported thermal efficiencies of 0.741 and 0.9, respectively. Meanwhile the work of Jiang et al., 2019 calculated one of 0.56. Proving major thermal capacities of concentrated solar technologies compared to conventional heating systems. Consequently, concentrated solar technologies have been proposed as an option for improving thermal efficiency, as well as reducing the environmental impact (Ayala-Cortés et al., 2020; Jiang et al., 2019).

2. Methodology

2.1 Solar reactor prototype

A solar reactor prototype of 644 mL was especially designed to operate at high radiative flux and high pressures. This solar batch reactor was used to perform the hydrothermal processing experiments. The head of the reactor has two standard fittings, where one type "K" thermocouple is placed to be in direct contact with the slurry. Additionally, a pressure transducer, a PT-100, a relief valve and system of inlet and outlet valves were used (Fig. 1). The reactor was placed in front of the concentrator, in the focal zone of the IER-UNAM solar furnace. The main characteristics of the IER-UNAM solar furnace can be found in a previous work (Ayala-Cortés et al., 2019).



Fig. 1: Diagram of the solar batch-reactor for hydrothermal processing of biomass.

Fibers of *agave angustifolia* bagasse were collected from the state of Guerrero, Mexico, where the plant grows and is used in the production of mezcal. In the cooking and distillation process most liquids are extracted from the plant, and at the end of the process residual biomass that has no use and usually ends on the ground, representing an important industrial waste. 20 g of bagasse fibers were added in the reactor with deionized water at a solid concentration of 10 wt.%. Once the reactor was sealed, Argon gas was injected three times to the system to remove the oxygen and achieve an inert atmosphere.

In the course of the solar HTP experiments, four type "K" thermocouples were placed in the irradiated face of the reactor. Experiments were performed at 150, 250 and 300 °C, with an average heating rate (HR_{av}) of 1.7 °C/min, residence time (τ) of 0 and 60 min, solid concentration of 10 wt.% and initial pressure of 10, 30 and 50 bar at ambient temperature. It is important to point out that the residence time is defined as the time that the target temperature is maintained.

2.2 Separation products

After the residence time has passed and the heating is finished, the reactor cools down at room temperature. Then, the outlet valves are slowly opened to reduce the internal pressure in the reactor. The gas products are vented to the atmosphere and the remaining product is collected without adding any extra solvents, this product consists in a mixture of aqueous phase, bio-oil and char. The separation process of the different products was accomplished

according to Fig. 2, after venting gas, the product goes through a filtration process to separate the aqueous phase. Next, the mix of char and oil are separated by Soxhlet extraction in acetone for 12 h. Then, both products, char and bio-oil in acetone are dried at 60 °C to remove the remaining acetone.



Fig. 2: Diagram of the separation methodology of the solar hydrothermal products.

The yield calculation uses the atomic carbon balance of each phase according to Eqs. (1) (2) and (3),

$$Y_{GasAq.phase}(\%) = (1 - Y_{Bio-oil} - Y_{Char})x100$$
 (1)

$$Y_{Bio-oil}(\%) = \frac{Bio-oil}{m_{Bagasse} \# c} x100$$
⁽²⁾

$$Y_{Char}(\%) = \frac{m_{Char} \# c}{m_{Bagasse} \# c} x100$$
(3)

Where $Y_{GasAq.phaseFaseac.}$ is the yield of the gas and aqueous phase obtained by difference, $Y_{Bio-oil}$ is the biooil yield, Y_{Char} is the char yield, $m_{Aceite} \# C$ is the carbon content in the bio-oil mass at constant weight, $m_{Char} \# C$, is the carbon content in the char mass and $m_{Bagasse} \# C$ is the carbon content in the raw biomass mass.

Additionally, high heating values (HHV) of char and bio-oil were calculated by Eq. 4 (Channiwala et al., 2002), as well as the energy recovery, ER, (Eq. 5) (Seehar et al., 2021).

$$HHV(MJ/kg) = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211Ash$$

(4)

 $ER(\%) = \frac{HHV product}{HHV biomass} xYi$ (5)

3. Results

3.1 Effect of the solvent extraction

In order to separate and recover most oil product after the hydrothermal process a solvent is required. Nevertheless, previous studies have found that the type of extraction solvent has a direct impact on the product yields (Watson et al., 2019; Lu et al., 2019). Consequently, two different solvents, Dichloromethane (DMC) and acetone, were used during the separation process. Figure 3 shows the oil and char yields obtained with DCM and acetone, both experiments were performed at 250 °C, with an initial pressure of 50 bar, 10 wt.% solid
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concentration and 60 min of residence time. The aqueous and gas phases were not included in this analysis because they do not have contact with the solvent extraction, as showed in the separation diagram (Fig. 2). Results indicate that DCM achieved a higher char yield than acetone (29% compared to 21%). However, there is a reduction in the oil yield (15% for DCM compared to 17% for acetone). This behavior has been previously reported by Lu et al., 2019, where different model compounds were used during HTP, such as cellulose, lignin and xylose. The authors suggest that some products of these model compounds are composed of ketones and phenol groups, and as acetone is also a ketone with the same polarity, it is easier to extract these substances. In the present work, the enhancement of using acetone during the oil recovery was around 13% in contrast with DCM. Therefore, acetone was used as extraction solvent during the product recovery process.



Fig. 3: Effect of solvent extraction (acetone and dichloromethane) during oil recovery. Operational parameters of the experiments: 250 °C, initial pressure of 50 bar, 10 wt% biomass concentration, heating rate of 1.7 °C/min and 60 min of residence time.

3.2 Effect of temperature

Table 1 shows the operational conditions of the different HTP experiments performed, where temperature and pressure are the analyzed parameters. Figure 4a) shows the influence of temperature on the yields, at 0 min of time residence, 10 wt.% solid concentration and 50 bar of initial pressure. It can be noticed that an increase of temperature reduced drastically the solid product, from 57 to 29%. In contrast, gas & aqueous phase along with oil yields are improved with temperature. Bio-oil yield increased from 9% at 150 °C, to 28% at 300 °C. Literature reports the same trend with lignocellulosic biomass. At lower temperatures, biomass starts to decompose and molecules break and to reorganize into lighter compounds [18]. In addition, most favorable oil yield is found near the critical point of water, in the range of temperature of 250-375 °C (De Caprariis et al., 2017; Guo et al., 2015; Zhang et al., 2010).

In the chemical content of the char and oil products (Table 2), it was observed that temperature increases carbon content from 56 to 69% in the oil, meanwhile, the oxygen is reduced from 52 to 45%, which directly impacts on the HHV of the crudes, being 23 MJ/kg at 150 °C and 28 MJ/kg at 300 °C, same behavior is also reported by Xue et al.; 2016. By comparing bio-oils from different thermochemical conversion processes, it was found that the oil produced in the present work shows and improvement against a typical bio-oil from pyrolysis process at 450 °C, due to pyrolysis bio-oils can have higher amount of moisture compared to bio-oils from HTP (Mohan et al., 2006), which have a negative effect on the HHV. Moreover, energy recovery reached its highest value for the char at 150 °C (65%), and the highest for oil at 300 °C (53%), which is related to the major yields of both products at these conditions, at lower temperatures superior amounts of char are expected, and by increasing temperature char decomposes and forms bio-oil.

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Ν	Conc. (wt. %)	τ (min)	T (°C)	P _i /P _f (bar)	HR _{av} (°C/min)
1	10	0	150	52/71	1.3
2	10	0	300	52/117	1.8
3	10	60	250	11/46	1.9
4	10	60	250	32/82	1.7
5	10	60	250	51/102	1.6

Tab. 1: Operational conditions of the different solar HTP experiments

3.3 Effect of pressure

Pressure is an important parameter that allows to maintain water under liquid state in the hydrothermal process (Ayala-Cortés et al., 2020). The highest pressure that can be obtained during HTP experiments is directly related to the initial pressure, therefore, in this work different initial pressures were studied (10, 30 and 50 bar). Once the target temperature (250°C) was reached the pressure inside the reactor increases up to 46, 82 and 102 bar, for an initial pressure of 10, 30 and 50 bar respectively. Figure 4b) shows that the most significant change is related to the gas and aqueous phase, which increases from 41 to 54%, whereas bio-oil and char yields tend to decrease, from 27 to 23% and from 32 to 23%, respectively. The decrease of char and bio-oil yields could be related to secondary reactions. As reported by Xue et al., 2015 a rise of pressure tends to form intermediates that decrease the oil production. Additionally, solar reactor has high temperature gradients, which could reduce biomass conversion and therefore increasing this negative effect on the char and oil production.

Table 2 shows that initial pressure has a minor effect on the bio-oil composition. On the other hand, the chars at 10 and 30 bar have comparable chemical content between them, but at 50 bar there is a decrease on the carbon content and an increase of oxygen, which results in a lower HHV. In this respect, it could be proposed that higher initial pressures are not necessary to obtain bio-oils with similar chemical characteristics. This reduces the pumping demand which could represent saving costs in a higher commercial scale. In terms of energy recovery of bio-oil, at 10 bar, energy recovery showed the highest value (56%), as pressure increases, energy recovery tends to decrease. On the other hand, the ER for the char is similar at 10 and 30 bar. However, at 50 bar the ER from the char decreases almost half compared to the one at 10 and 30 bar.



Fig. 4: Influence of the experimental conditions on yields as function of a) temperature ($P_o = 51.5 \text{ bar}/P_{out} = 92.1 \text{ bar}, \tau = 0 \text{ min}, \text{HR}_{av} = 1.6 ^{\circ}\text{C/min}$ and 10 wt% solid concentration) and b) initial pressure ($T_{av} = 258 ^{\circ}\text{C}, \tau = 60 \text{ min}, \text{HR}_{av} = 1.6 ^{\circ}\text{C/min}$ and 10 wt% solid concentration).

Ν	C (wt. %)	H (wt. %)	O (wt. %)	HHV (MJ/kg)	ER (%)
1	43/56	5/6	52/37	16/23	65/14
2	52/69	4/6	45/25	17/28	33/53
3	57/68	4/6	39/26	20/28	42/56
4	57/69	4/6	39/25	20/28	43/52
5	52/69	4/6	44/25	18/28	26/44

Tab. 2: Chemical composition of the char/bio-oil at different operational conditions.

Raw b	45	5	49	16	Ash 11%

4. Conclusion

Solar hydrothermal processing of biomass was successfully performed to analyze the influence of the operational parameters on the yields. Main results indicate that using acetone as solvent extraction can improve the bio-oil recovery up to 13% compared to dichloromethane. Additionally, it was found that bio-oil yields up to 28% can be obtained at 300 °C with residence time of 0 min. At the same time, it was found that an initial pressure of 50 bar tends to reduce the bio-oil yield, which indicates that lower initial pressures are better to improve yields. Furthermore, a decrease in the initial pressure can lead to save costs on a further commercial scale.

Acknowledgments

Authors would like to acknowledge the support of R. Morán-Elvira for the operation of SEM, M. L. Ramón-García and P.E. Altuzar-Coello for XRD measurements, M. Baas López for CHONS analysis, and J.J. Quiñones Aguilar for solar furnace maintenance. The authors acknowledge the financial support received from Fondo Sectorial CONACYT-SENER Sustentabilidad Energética through Grant 207450, "Centro Mexicano de Innovación en Energía Solar (CeMIE-Sol)", within strategic project No. 120 "Tecnología solar para obtención de productos con valor agregado mediante procesamiento hidrotermal", and DGAPA PAPIIT-UNAM IN110118 "Producción de bioaceites a través del uso de microalgas y energía solar concentrada". H.I. Villafán-Vidales also acknowledge the financial support of DGAPA-UNAM through the PASPA program.

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G-01. Integration of Variable Renewable Energy into large grids

Artificial Intelligence-Based Approach for the Control of PMSG Based Wind Energy System

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Abstract

Assessment of wind energy potential is extremely important before installation of wind turbine (WT) in any location. However, the intermittency of wind speed makes it more difficult to estimate the power potential. Thus, in this paper, two intelligent machine learning techniques namely neural network (NN) and adaptive neuro-fuzzy inference system (ANFIS) were employed to estimate the maximum power from the wind turbine and generates a reference torque to drive the rotor of PMSG. A comparative analysis for both NN based WT and ANFIS based WT is presented, while NN based WT estimated more accurate power than the ANFIS based WT. The NN based WT showed an error as low as 0.039% while ANFIS based WT shows 0.453%. Thus, the NN based WT model is selected and coupled with the PMSG system and is tested using wind data recorded at 100 meters height for Yanbu city, KSA. The PMSG was implemented with speed control mode using a PI controller which makes the NN-WT-PMSG effectively tracks the reference rotor speed and torque and generate proportional electromagnetic torque.

Keywords: Wind turbine, Wind Energy Conversion, Neural Network, Adaptive Neuro Fuzzy Inference System, PMSG Control

1. Introduction

Renewable energy (RE) had secured a prominent position in the global energy sector in response to the rise in electricity demand and carbon emission from conventional power generation. The RE market witnessed a total installed power capacity of 2,800 GW from Solar, Wind, Hydro, and other RE resources by 2020 (IRENA, 2021). The total wind capacity as of 2020 was around 733 GW, representing almost 26.2% of the total RE capacity. It is evident from Fig. 1 that the wind energy systems had significantly contributed to the modern RE market as well less assisted the energy market in minimizing the carbon emissions. For almost a decade China has been leading the wind energy market and stands top in 2020 with an installed capacity of 282 GW followed by the USA and Germany with 118 GW and 62 GW respectively (IRENA, 2021). The five leading counties in terms of wind installed capacity is shown in Fig. 2. These five countries also cover almost 72% of global installed wind capacity in 2020.



Fig. 1: Installed capacity share from Wind energy and Rest of RE capacity



Fig. 2: Wind capacity leader based on the capacity installed in 2020

Assessment of wind potential is a key step that drives the successful installations of wind turbines (WT) in any location. Kingdom of Saudi Arabia is an arid or desert land with a long period of summer than winter but has a high potential for the deployment of a wind turbine. With the ambitious target KSA Vision 2030, to meet 50% of its energy needs from renewables by 2030, which 16 GW is aimed to generate from wind plants (REPDO, 2019). The wind speed has been monitoring by King Abdullah City for Atomic and Renewable Energy (K·A·CARE) over time for selected sites within KSA such as Al-Jouf, Riyadh, Jeddah, Yanbu (K·A·CARE, 2021). The average wind speed in KSA at 100 meters height ranges between 5.3 m/s to 8.4 m/s (Ghamdi, 2020). North of Yanbu city in KSA witness higher wind speed than any other location where the monthly average wind speed ranges between 6.8 m/s to 11.43 m/s at 100-meter height (K·A·CARE, 2021). Dumat al Jandal plant located in Al-jouf has a planned capacity of 400 MW from wind generation emerged as the first utility-scale wind farm (Saudi Gazette, 2020). Other wind farms are also under the predevelopment stage which includes Yanbu (850 MW) and Midyan (400 MW) projects as per the national renewable energy program (Rahman et al., 2021; REPDO, 2019). Thus, there is an extensive need to assess the potential of power generations in KSA utilizing wind resources.

Today, the energy generated from wind turbines is not only used for off-grid and on-grid power generations but also other applications such as desalination (Campione et al., 2020). In the modern world WT are available in two different kinds of namely WT exist in the market based on their axis of rotation ie; the vertical axis and horizontal axis WT. Each type of WT has its pros and cons which are subjected to location, size, application, etc., (M. Saad, 2014). Further, the wind energy conversion system (WECS) is classified based on the type of generators used, permanent magnet synchronous generators (PMSG), and doubly-fed induction generators (DFIG) (Yin et al., 2007). Due to its better efficiency and good power quality of variable speed wind turbine (VSWT) generators fed by PMSG are usually preferred. The wind turbine produces power while subjected to wind speed bounded by cut-in and cut-out wind speed (Baseer, 2017). Over the years the wind turbines had witnessed significant improvements in their size, aerodynamics design, blade structure, overall efficiency of wind speed which makes difficult for power system operators and designers to accurately size the wind turbine (Njiri and Söffker, 2016). The impact on the power system in terms of efficiency, reliability, the transmission was addressed (Albadi and El-Saadany, 2010; Shi et al., 2014).

The power generated from the wind turbines is not only dependent on the wind speed but also several parameters such as tip speed ratio, length of the blades, wind direction, air density rotor speed, type of generator systems. To tackle the challenge of intermittency of wind speed, many researchers have employed several maximum power point tracking (MPPT) algorithms. The most common technique for MPPT algorithms are tip speed ratio (TSR) control, perturb and observe (P&O), power signal feedback (PSF) control, optimal torque (OT) control, and several other algorithms (Abdullah et al., 2012; Kumar and Chatterjee, 2016). Many control methods were used in the literature to name a few are pitch angle controller, grid side inverter controller, MPPT controller (Wang et al., 2014; Yin et al., 2007). Machine learning techniques such as neural networks (NN) and adaptive neuro-fuzzy inference systems (ANFIS) are also used for estimating or predicting wind speed (Chang et al., 2017; Khosravi et al., 2018). Abo-Khalil and Lee proposed MPPT control of wind energy systems by estimating the wind speed based on support vector regression (Abo-khalil and Lee, 2008). This technique was found to be less effective with an error of 3.3%. However, forecasting the wind speed will only help to determine the wind power but since the

real system is coupled with the generator, it is extremely important to realize the overall effect on the WECS. On the other side, researchers have also developed control strategies for PMSG based wind turbines by using adapting sliding mode control to track the reference speed (Lee and Chun, 2019) while Kim et al presented tuning methods for PI controller parameters of PMSG wind turbine (Kim et al., 2015).

In this work, two intelligent techniques namely NN and ANFIS were employed to estimate the maximum power from the wind turbine and generates a reference torque to drive the rotor of PMSG. This was done by coupling the PMSG with the NN/ANFIS based WT models. The PMSG system operates in the speed control loop where the PI controller is fed with the error signal arising as a difference between the actual PMSG rotor speed and the reference speed generated from NN/ANFIS based wind turbine model. The performance of the proposed method is tested at first by subjecting experimental wind data from Yanbu city from KSA. The city is selected because it is the city with highest average wind speed and the government in KSA has already selected the city for future projects of a wind farm, which makes more important to assess the wind power potential.

2. Wind Energy Conversion System (WECS) Modeling

The WECS modeled in this work comprises a wind turbine coupled with PMSG and power conditioning units represented by 'm' as shown in Fig. 3. The rotor of the wind turbine is coupled with the PMSG rotor and then to power inverters. The brief model of each component of WECS is described in this section.



Fig. 3 Simplified representation of WECS model

2.1 Wind Turbine

The kinetic energy from the wind is translated into rotational motion due to the design of the turbine blades. This mechanical form of rotational energy is converted into electrical energy by means of a turbine generator (Sohoni et al., 2016). The expression for the theoretical mechanical power is given by (eq.1)

Mechanical aerodynamic power
$$(P_m) = \frac{1}{2} \rho A V_w^3 C_p(\lambda, \beta)$$
 (eq.1)

Where, ρ is the density of air, A is the swept area of the turbine blade, V_w is the velocity of wind, C_p is the coefficient of power defined by the function of tip speed ratio (λ) and pitch angle (β). (Eq. 2) describes the relation of tip speed ratio with turbine rotor speed ω_r , rad/sec), wind speed and length of blade (R).

$$\lambda = \frac{\omega_T R}{V_w} \tag{eq.2}$$

The power coefficient is also a function of λ and β , given by (eq.3), while the iterative tip speed ratio (λ_i) is given by (eq.4)

$$C_p(\lambda,\beta) = 0.22 \left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{\frac{-12.5}{\lambda_i}} + 0.0068\lambda$$
(eq.3)

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$
(eq.4)

The mechanical torque (T_m) generated from the wind turbine is given by (eq.5)

$$T_m = \frac{P_m}{\omega_r} \tag{eq.5}$$

2.2 Estimating of MPPT for turbine

Maximum power from the wind turbine is achieved when the coefficient of power is the highest corresponding to the optimal tip speed ratio. Several kinds of literatures proposed that when the blade pitch angle is at zero, the maximum power at a given speed is achieved (Kim et al., 2015; Wang et al., 2014). Optimum tip speed ratio (λ_{opt}) also determines the optimum rotor speed (ω_{opt}) and which the turbine operates corresponding to maximum power (P_{max}) . Both the expressions for (P_{max}) and (ω_{opt}) are given by (eq. 6) and (eq.7) respectively. The relation between the turbine power and turbine speed is shown in Fig. 4.



Fig. 4 Relation between the turbine speed and the power generated from turbine

2.3 PMSG

A three-phase permanent magnet synchronous machine is having its stator winding connected in Wye to the point of internal neutral while the rotor can be salient pole or round. When a negative torque is provided the machine operates in generator mode. A three-phase sinusoidal model can be expressed in the d-q frame of reference (MATLAB, 2021a). The equations governing these models are given in (eq.8) to (eq.10).

$$\frac{\mathrm{di}_{\mathrm{sd}}}{\mathrm{dt}} = -\frac{\mathrm{R}_{\mathrm{sa}}}{\mathrm{L}_{\mathrm{sd}}}i_{\mathrm{sd}} + \omega_{\mathrm{s}}\frac{\mathrm{L}_{\mathrm{sq}}}{\mathrm{L}_{\mathrm{sd}}}i_{\mathrm{sq}} + \frac{1}{\mathrm{L}_{\mathrm{sd}}}V_{\mathrm{sd}}$$
(eq.8)

$$\frac{\mathrm{di}_{\mathrm{sq}}}{\mathrm{dt}} = -\frac{\mathrm{R}_{\mathrm{sa}}}{\mathrm{L}_{\mathrm{sq}}}i_{\mathrm{sq}} - \omega_{\mathrm{s}}\left(\frac{\mathrm{L}_{\mathrm{sd}}}{\mathrm{L}_{\mathrm{sq}}}i_{\mathrm{sd}} + \frac{1}{\mathrm{L}_{\mathrm{sq}}}\psi_{\mathrm{p}}\right) + \frac{1}{\mathrm{L}_{\mathrm{sq}}}V_{\mathrm{sq}} \tag{eq.9}$$

$$T_{e} = \frac{3}{2} * \frac{P}{2} \left[\psi_{p} i_{sq} + i_{sd} i_{sq} (L_{sd} - L_{sq}) \right]$$
(eq.10)

Where V_{sd} , V_{sq} , I_{sd} and I_{sq} are the d-q axis stator voltages and currents, respectively. L_{sd} and L_{sq} are the inductances of the generator. P is the number of poles, ψ_p is the permanent flux, stator resistance is represented as R_{sa} and ω_s is the generator's electrical angular frequency. T_e is the electromagnetic torque.

2.4 Machine learning technique

Several machine learning techniques have emerged over the decades but in this section, two technique, will be discussed considering their use in the approach.

- (i) Neural Network
- (ii) Adaptive neuro fuzzy inference system

Neural network (NN): It is also known as artificial neural network (ANN) is an intelligent technique that resembles a human brain by interconnecting biological neurons or nodes to perform complex computation. They learn from a set of trained data and generates the ability to predict future events (Cao et al., 2018). In several engineering applications, some of the types of NN include feedforward neural network (FFNN), Convolution neural network (CNN), and recurrent neural networks. Typically, FFNN comprises a set of inputs layers, one or more hidden layers, and an output layer (MATLAB, 2021b). During the learning process input and output candidates need to

be explicitly defined and in this phase of learning weights are adjusted and the output is estimated by minimizing the error. Upon successful training of the process, testing can be performed to verify the accuracy of the learning process. In general, there are no limitations in selecting the number of input and output candidates.

Adaptive neuro-fuzzy inference system (ANFIS): This method is a hybrid learning process where the input and output data mappings are based on if-then rules (human knowledge) and stipulated input-output pairs (Jang, 1993). It combines the neural network and fuzzy logic principles with the advantage of seeking benefit from both frameworks. The architecture of ANFIS comprises five layers. The first layer accepts the input values by defining some membership functions also called fuzzification. The second layers are the rule layer where a set of rules are generated. The third layer normalizes the layer which is provided to the fourth layer. Finally, the fifth layer is the defuzzification layer to return the final output. The Takagi-Sugeno cannot accept only single-output (MATLAB, 2021c).

3. Methodology

In the proposed methodology of a NN or ANFIS based WT coupled with a PMSG system, the following steps are followed.

- 1. Generating a data set from a wind turbine.
- 2. Training NN and ANFIS model
- 3. Implementing speed control of NN/ANFIS based wind turbine PMSG model

Upon successful completion of the above three steps, the developed strategy is used to explore the wind energy potential for Yanbu city of KSA.

3.1 Data set generation of wind turbine

The data set for a wind turbine is generated by using the model eq.1- eq.4. As the mechanical power obtained from the wind turbine is a cubic function of wind speed as well as an indirect function of tip speed ratio (λ), a range of wind speed is selected from 3-19.5 m/s and the range of tip speed ratio is selected from 0.1 - 14. Both the wind speed and tip speed ratio were classified into 280 samples, to generate a matrix to obtain a 280×280 matrix for power. Each row of the power matrix represents the power at one point of wind speed with 280 samples of tip speed ratio. Thus, from each row, a maximum power point is obtained which corresponds to the optimal tip speed point. Similarly, the optimum turbine speed is obtained at the optimal value of tip speed ratio. Finally, as an output of this wind turbine model, 280×1 matrix for maximum power (P_{max}) and optimum rotor speed ω_{opt} is selected.

3.2 Training if NN and ANFIS

The training for both NN and ANFIS starts with defining the inputs and outputs for the model. Clearly, from the data set generation process, sampled wind speed is selected as input while the matrix for maximum power (P_{max}) and optimum rotor speed ω_{opt} is taken as output.

3.2.1 NN training:

In the process, single input and dual output is selected and the model are trained by using a backpropagation algorithm. Ten neurons were selected in the hidden layer between the input and output layer as shown in Fig. 5. Upon successful training process is completed the model becomes a neural network wind turbine model which is capable to estimate maximum power and optimal speed at any wind speed defined within the limits.



Fig. 5 Simplified representation of Neural network wind turbine model

3.2.2 ANFIS Training

The training process of ANFIS is also similar to NN in terms of defining input and output. However, the ANFIS model is a bit complex than NN as it only accepts a single output, unlike NN. As a result, two ANFIS structures were created one for maximum power output and the second for the speed output. The ANFIS power model is formed by using 10 membership functions in the intermediate layer while the ANFIS speed model is formed by using 5 membership functions. The simplified ANFIS wind turbine model is depicted in Fig. 6



Fig. 6 Simplified representation of ANFIS wind turbine model



The strategy to control of PMSG based NN/ANFIS wind turbine in such a way that the torque output generated from the NN or ANFIS based wind turbine model is coupled to a permanent magnet synchronous machine. The negative torque is provided to the machine to operate in generator mode. The PMSG is connected to other power conditioning units such as the PWM inverter and provides the electromagnetic torque (T_e). The strategy implemented to control is presented in Fig. 7. The speed control method adopted is modeled in the d-q frame of reference. Two control loops were designed, the first outer loop is to control the PMSG rotor speed while the inner loop is to control the PMSG stator current. Hence in the outer loop by means of PI controller a reference direct axis current (i_{qref}) is generated by feeding back the error signal from the difference of NN/ANFIS model and PMSG. The reference quadratic axis current (i_{dref}) is selected as zero. The current is transformed back into three phases from the d-q reference and a three-phase reference current (i_{abcr}) is feedback to PWM inverter.



Fig. 7 Proposed control NN/ANFIS based wind turbine PMSG system

4. Results and Discussion

The approach and the methodology presented in the previous section are used to perform simulation in MATLAB/SIMULINK. The input data for the wind speed was collected in the form of monthly average from King Abdullah City for Atomic and Renewable Energy (K·A·CARE) station located in the north of Yanbu (24.34202 ° N, 37.48446° E), KSA. Two separate simulations were performed for NN based wind turbine PMSG

model and ANFIS based wind turbine PMSG model. The sampling time selected during the simulation was 2 µs. The profile for monthly average wind speed for Yanbu location is shown in Fig. 8. With respect to the input wind speed, the NN based WT model, as well as ANFIS, based WT estimated the mechanical power and mechanical torque. Fig. 9 shows the power and torque response of the NN based WT model and Fig. 11 shows the power and torque response of the ANFIS based WT model.



From Table 1, it can be observed that the maximum power was achieved to be 1.12 MW in June in which the highest wind speed was recorded while the lowest power was estimated in October with 0.23 MW. The mechanical power estimated by the NN based wind turbine shows a maximum error of 0.039% while the power estimated by ANFIS based wind turbine shows 0.453 %. Moreover, the ANFIS model is very complex as it involves separate models for speed and power. As a result, several membership functions need to be defined which increases the computation time while performing the simulation. On the other hand, NN based model requires less time for the computation and at the same time, it is more robust than the ANFIS model.

Month	Wind speed (m/s)	Theoretical calculated Maximum power (MW)	Mechanical power generated from designed NN model (MW)	Error (%)	Mechanical power generated from designed ANFIS model (MW)	Error (%)
Jan	7.9	0.37005	0.3700	0.014%	0.37115	0.297%
Feb	7.5	0.32250	0.32250	0.000%	0.32204	0.143%
Mar	10.1	0.7752	0.7749	0.039%	0.77871	0.453%
Apr	10.4	0.83636	0.83633	0.004%	0.83657	0.025%

Tab. 1: Comparison of NN-WT and ANFIS-WT model using actual wind speed data

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May	8.3	0.43732	0.43730	0.005%	0.43836	0.238%
Jun	11.4	1.1270	1.12699	0.001%	1.1276	0.053%
Jul	9.3	0.61054	0.610487	0.009%	0.609596	0.155%
Aug	10.2	0.79316	0.793272	0.014%	0.79419	0.130%
Sep	10.7	0.92603	0.92598	0.005%	0.92486	0.126%
Oct	6.8	0.23791	0.237941	0.013%	0.23788	0.013%
Nov	7.2	0.28218	0.28219	0.004%	0.280916	0.448%
Dec	8.0	0.38487	0.38488	0.003%	0.38626	0.361%

Further NN based WT- PMSG model is selected to study the effect of the combined NN model with PMSG. Fig. 11 shows that the speed control of the combined NN based WT- PMSG model is very effective in terms of following the reference rotor speed generated from the NN based WT model. The electromagnetic torque generated from the PMSG model as shown in Fig. 12 also follows the torque profile set by the NN based WT model. The noisy behavior of the electromagnetic torque is due to the presence of noise in the PMSG stator current due to the use of a PWM inverter. However, the angular speed of PMSG does not have noisy behavior as it is prevented by the inertia of the generator. The profile for the voltage of the PWM inverter is shown in Fig. 13.



Fig. 11 Tracking of PMSG speed and reference speed from NN based WT- PMSG model



Fig. 12 Electromechanical torque generated from NN based WT- PMSG model



Fig. 13 PWM inverter voltage generated from NN based WT- PMSG model

5. Conclusions

In this paper, a novel control strategy is developed to control a permanent magnet synchronous generator (PMSG) coupled to a neural network and adaptive neuro-fuzzy inference system wind turbine model. The model is tested to assess the wind power potential in Yanbu city of Saudi Arabia. To machine algorithms (NN and ANFIS) are used and NN based WT model was found to be more robust as it is capable to estimate the power more accurately with an error as low as 0.039% when compared to 0.0453% error from ANFIS based WT. Moreover, the computation time needed by the ANFIS approach is 20 times more than the NN approach because of its complex structure. Further, NN based WT is used to provide a reference speed and torque to drive the PMSG rotor which is controlled by means of a PI controller. The Electromechanical torque and speed of the PMSG rotor effectively follow the input wind speed profile. Thus, this study helps to assess the actual power potential of a given wind data which is a primary step towards the deployment of wind turbines.

6. Acknowledgements

Authors like to thank Interdisciplinary Research Center for Renewable Energy and Power Systems (IRC-REPS), Research Institute, King Fahd University of Petroleum & Minerals, (KFUPM), Dhahran 31261, Saudi Arabia. Mohammed Kamal Hossain acknowledges the support received under Interdisciplinary Research Center for Renewable Energy and Power Systems (IRC-REPS) Grant INRE2114. King Abdullah City for Atomic and Renewable Energy (KACARE) is acknowledged for providing the wind speed station data.

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Hour-Ahead Bivariate and Multivariate Solar PV Power Forecasting for Effective Grid Integration

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Abstract

For an effective grid integration of large-scale solar PV plants and their market participation, accurate power forecasting is very crucial. System operators use power forecasting to maintain power system security and reliability with economic energy dispatch. Machine learning models like Support Vector regression (SVR) are popularly used in short-term forecasting for better accuracy than other artificial intelligence (AI) models. However, SVR models need large amounts of data and involve very complex computations to achieve better accuracy. To address these problems, this research aims to develop an SVR model improved by integrating the non-linear least square Gauss-Newton method (SVR+GN) for hour-ahead solar PV power forecasting with a five-minute resolution. The performance of this model was verified in bivariate and multivariate modes by comparing the forecasting results with SVR, non-linear and persistence models on sunny, partly sunny and overcast days. To further verify the accuracy of SVR+GN, SVR, persistence and non-linear models, error evaluation parameters like Mean Absolute Percentage Error (MAPE), Mean Relative Error (MRE), Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were used. The improved SVR model needed fewer data and simpler computations for training and it achieved better accuracy even on overcast days. This is extremely useful for efficient grid integration and market participation of solar PV plants.

Keywords: Bivariate, Hour-ahead Forecasting, Multivariate, Power Forecasting, Solar PV, Solar Power Forecasting, Support Vector Regression (SVR)

1. Introduction

For system operators, accurate forecasting is of utmost importance for economic dispatch, power system planning and management to ensure power system reliability and security ((AEMO); Forecasting). Accurate forecasting helps solar PV plants to bid in the electricity markets and provide electricity with minimum curtailment and financial penalties. Power system operators use day-ahead electricity markets for unit commitments and economic electricity dispatch decisions. Hour-ahead electricity markets are mainly used for market clearing, precise dispatch for power system security and reliability, ancillary services and reserves procurement (Das et al., 2018; Ross Gillett, 2018). For effective grid integration and market participation, renewables like solar PV need accurate power forecasting.

Abundant research has been conducted in direct i.e. solar power forecasting and indirect i.e. solar irradiance forecasting with different time horizons. In the last decade, machine learning techniques like Support Vector Regression (SVR) are popularly used in short-term forecasting because of their high accuracy and less computational complexity. Various error parameters are used for these forecasting models to validate their performance. Alfadda et al confirmed that for hour-ahead solar PV power forecasting, the SVR model performs 2.6% better than the Lasso regression and linear regression forecasting models. Root Mean Square Error (RMSE) method is used for comparing the performance of these models (Alfadda et al., 2017). Performance of SVR and Random Forest (RF) models are verified in (Yen et al., 2018) using Mean Absolute Error (MAE), RMSE, Mean Forecast Error (MFE) and Mean Absolute Scaled Error (MASE). Using these error parameters, the authors observed that RF achieves 37 to 40% better accuracy than the SVR model. It was concluded from the results that RF tends to overestimate while SVM tends to underestimate the hour-ahead solar PV forecasting. (Guermoui et al., 2021) investigated incorporating SVR with least square methods to build hybrid models for 1 to 12 hours ahead solar forecasting and evaluated their performance using RMSE, relative RMSE (rRMSE), Mean Absolute Bias Error (MABE) and correlation coefficient (r). Results showed that using Artificial Bee Colony optimisation

to solve least square equations in SVR can improve the accuracy of solar forecasting.

However, all these SVR and hybrid SVR models use a very large amount of data for training to achieve better accuracy and are computationally very complex. (Yen et al., 2018) also recommended that if more data is used for processing and training the model, it will help to further improve the accuracy of the models. To address these issues, this research aims to develop an SVR model improved by integrating the non-linear least square Gauss-Newton (GN) method for hour-ahead solar PV power forecasting with a five-minute resolution. The performance of the presented model is verified using the similar error parameters used in above mentioned research.

The organization of the rest of the paper is as follows. A review of solar PV power forecasting methods is presented in section 2. Section 3 provides a methodology of the SVR+GN model, residual monitoring and error parameters used for analysis. Results and error analysis are discussed in section 4. And finally, in section 5, the conclusions are summarized.

2. Solar PV Power Forecasting Methods

There are numerous methods present in the literature for forecasting. Depending on the type of the technique used for forecasting, the forecasting methods are mainly categorized into four types i.e. Physical, Statistical, Artificial Intelligence (AI) and Hybrid (Antonanzas et al., 2016; Das et al., 2018; Voyant et al., 2017; Wan et al., 2015). Configuration of forecasting methods depending on these four techniques is shown in Fig. 1.



Fig. 1: Solar PV Power Forecasting Methods

Physical methods use numerical weather prediction (NWP) data along with PV plant characteristics like the location of the plant and orientation data to forecast solar irradiance and this forecast is then used to calculate solar PV power output. Physical methods may not need historical data for solar irradiance and power output of the PV plant but their accuracy is highly dependent on the quality of NWP data. Models like Global Forecast System (GFS), MM5 fall under this category and are used for forecasting solar irradiance to further calculate solar PV power.

Statistical methods use historical data of solar irradiance, NWP and power output to calculate the relation between these data to train the model and this model is then used with future NWP data to forecast PV output power. These

methods are complex mathematical methods and to achieve higher forecasting accuracy, one has to compromise on pre-processing of large training data and complexity of these models. Methods based on time series analysis and regression analysis e.g. Auto-Regressive Moving Average (ARMA), Auto-Regressive Integrated Moving Average (ARIMA), Auto-Regressive Integrated Moving Average with Exogenous variable (ARMAX) and Auto-Regressive with Extra input (ARX) are the statistical methods.

AI methods like SVR, Artificial Neural Networks (ANN) are commonly used in solar forecasting. SVR is mostly popular because of its better accuracy than other AI methods (Antonanzas et al., 2016). Forecasting models using AI methods do not need PV plant characteristics data like physical methods and are easy to model.

In hybrid methods, either two or more statistical methods, statistical methods with physical methods, pre or post data processing with statistical or physical methods are used to improve the accuracy of the forecasting. However, all this complex processing results in higher computational cost, data processing time and requires a large amount of training data.

For hour-ahead forecasting, there is a need for a solar PV power forecasting model which requires less amount of data for training, has less computational complexity while providing better accuracy than the models using the above explained forecasting methods. To suffice this need, the SVR+GN model is proposed in this research. The methodology of this proposed model is described in detail in the section below.

3. Methodology of SVR+GN

The SVR+GN model was developed by integrating the non-linear least square Gauss-Newton (GN) method with a simple SVR method for hour-ahead solar PV power forecasting with a five-minute resolution. This model is roughly based on the previous work (Pawar et al., 2020). The SVR+GN model was further improved for hour-ahead power forecasting. Also, the training of the model was monitored to improve the accuracy. The SVR+GN model can be used to operate in both bivariate and multivariate modes. In bivariate form, only solar insolation and solar PV power output data were used to train and test the model. In multivariate mode along with solar insolation and solar PV power output, temperature and humidity data were also provided.



Fig. 2: Flowchart for Forecasting using the SVR+GN Method

As shown in the flowchart of the SVR+GN in Fig. 2, historical data of solar insolation, temperature, humidity and solar PV power output were provided to this proposed model during the training phase depending on its mode of operation. These data were then classified according to three different weather conditions i.e. sunny, partly cloudy and overcast using standard deviation calculated for daily solar insolation data using eq. 1.

$$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{N}}$$
 (eq. 1)

 σ is the standard deviation value, x_i denotes the data points, μ is the mean of the data and the total number of the data points on the day is denoted by N.

The standard deviation of the data provides the amount of variation in the data. The solar insolation tends to be steady on a sunny day while it varies with few peaks and troughs on a partly cloudy day. On an overcast day, the solar insolation data varies greatly with more peaks and troughs. Hence, according to the value of standard deviation for the solar insolation, the data were classified in three different weather conditions. For sunny weather, the standard deviation was in the lowest range from 1 to 9. The standard deviation ranging from 9 to 70 was considered for partly cloudy weather whereas, for overcast conditions, the standard deviation of 70 and above was used for classification as shown in Tab. 1.

Standard Deviation Value Range	Weather Condition
1 to 9	Sunny Day
9 to 70	Partly Cloudy Day
70 and above	Overcast Day

Tab. 1: Classification of Data in Three Different Weather Conditions

Next, the sine kernel function given in eq. 2 was used in the SVR+GN model instead of the radial basis function which is generally used in a simple SVR model.

$$f(x,t) = x_1 * \sin(x_2 * t + x_3) + x_4$$
 (eq. 2)

Initial guess values for x_1 , x_2 , x_3 and x_4 in eq. 2 were provided to train the model using solar insolation, power output, temperature and humidity data. To solve the non-linear least squares problem, the Gauss-Newton method was used (Hartley, 1961; Heath, 2018). This method is known to find convergence in fewer than 12 steps. Once the solution was found the weighted factors for each data were calculated. These calculated weighted factors were then used in the testing phase to determine the solar PV power output using the data of solar insolation, temperature and humidity depending on the bivariate or multivariate mode of operation.

3.1. Residual Monitoring

Over-fitting and under-fitting of the data lead to lower accuracy. However, this was monitored in the training phase in the SVR+GN model using the residual function. The equation for the residual function is given in eq. 3 below.

$$r_i(x) = y_i - f(t_i, x)$$
 (eq. 3)

Where i = 1, ..., m; r(x) is the residual values for data y i.e. the data provided to the model and f(t,x) are the trained data values. To easily interpret the residual or how well the model was trained for given data, graphs of the input data and trained data were plotted. Random samples of these graphs are shown in Fig. 3. Blue curves in the graph represent original input data provided to the model during the training phase whereas red curves represent the trained values of that data.

As seen in the graphs below, if the data for sunlight, solar PV power, temperature and humidity are fluctuating over the period, data fitting in the training phase is also affected giving high residuals. This is mostly observed

here in samples Fig. 3(b) and Fig. 3(d). This eventually adds up to the forecasting errors and the accuracy of the forecasting is greatly affected.



Fig. 3: Graphs of Trained vs Original Input Data for (a) Sunlight, (b) Power, (c) Temperature and (d) Humidity

3.2. Forecasting Error Analysis

As the SVR+GN model used both SVR and the non-linear GN method, the forecasting results for the SVR+GN model were compared with simple SVR and non-linear models to verify whether the proposed model can improve the accuracy of these individual models. In short-term forecasting, generally, persistence forecast is used to compare the performance of forecasting methods, therefore, the persistence model was also used for comparison in this research.

The simple SVR model was developed using radial basis function kernel as shown below in eq. 4 where x_1, x_2 are the data points, $||x_1-x_2||$ is the Euclidean distance between data points x_1, x_2 and σ is the hyperparameter or the width of the kernel.

$$f(x_{1,}x_{2}) = e^{\frac{-||(x_{1}-x_{2})||^{2}}{2\sigma^{2}}}$$
 (eq. 4)

For a non-linear model, a simple non-linear function shown in eq. 5 was used.

$$y = b_1 + b_2 * (x)^{b_3}$$
 (eq. 5)

Where b₁, b₂, b₃ are coefficients whose values were provided in the algorithm, x is the matrix of the data set.

A persistence model is very simple and was developed as per eq. 6 given below. It considers that the value of forecasting at time t+1 will be equal to the value of the parameter at time t.

$$x_{t+1} = x_t \tag{eq. 6}$$

To further quantify and validate the performance of the SVR+GN model, error analysis of the forecasted power using SVR+GN, SVR, Non-linear and Persistence models was performed. Error parameters used in this research were Mean Absolute Percentage Error (MAPE), Mean Relative Error (MRE), Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). Eq. 7 represents the formula for MAPE while formulae for MRE, RMSE and MAE are given in eq. 8, eq. 9 and eq. 10 respectively.

$$MAPE = \frac{1}{N} \sum_{I=1}^{N} \frac{|P_{estimated} - P_{actual}|}{P_{actual}} * 100\% \quad (eq. 7)$$

$$MRE = \frac{1}{N} \sum_{I=1}^{N} \frac{|P_{estimated} - P_{actual}|}{P_{installed}} * 100\% \quad (eq. 8)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (P_{estimated} - P_{actual})^2} \quad (eq. 9)$$

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |P_{estimated} - P_{actual}|$$
 (eq. 10)

Here, N is the number of measurements, P_{actual} is the original or actual power output of the solar PV plant, P_{estimated} is the estimated power of solar PV plant using forecasting models and P_{installed} is the total installed capacity of the solar PV plant.

3.3. Data for Forecasting

To verify the reliability and robustness of these models, the estimated power using all these models was compared with the actual output power of The University of Queensland, Australia (UQ)'s 2.3MW solar PV. A month-long data was used to train the SVR+GN model in the training phase. Whereas, three different weather days were used for model verification that was outside of the training phase data. Dataset used in this research comprised solar insolation, PV power output, temperature and humidity data for the UQ solar. The data were available for every minute of the day, however were averaged to five minutes for this research. Section 4 will present the results and discussion on the performance of the SVR+GN model using UQ solar PV data.

4. Results and Discussion

As discussed in section 3, an hour-ahead bivariate and multivariate solar PV power forecasting model (SVR+GN) was developed by integrating the SVR with Gauss-Newton (GN) method. Performance of SVR+GN, simple SVR, non-linear and persistence models was verified in three different weather conditions i.e. sunny, partly sunny and overcast days. This research focuses on solar PV power forecasting for the energy market participation of the solar plants. For the bidding purposes, every hour the solar plants need to provide an hour ahead forecast with five minutes resolution. Therefore, the solar PV power forecasting graphs are presented as a random sample of hourly forecasting with a five-minute resolution. Error analysis for the proposed model was performed using the formulae from section 3.2.

4.1. Bivariate Mode

In bivariate mode, the SVR+GN model was trained and tested using only solar irradiance and power output data. Fig. 4 shows hour ahead solar PV power forecasting using SVR+GN, SVR, persistence and non-linear models in a bivariate mode. From these graphs, it can be seen that the models perform differently in all three different weather conditions.

On a sunny day, the proposed SVR+GN model was able to perform better than the simple SVR and non-linear model. However, the persistence model performed better than the SVR+GN model in sunny weather. On the partly sunny day, the SVR+GN model did not seem to be performing up to the mark and the other three models in comparison seemed to perform better. However, on an overcast day, the SVR+GN model was able to perform better than SVR, non-linear as well as persistence model. It is clearly visible from the graph in Fig. 4(c) that the forecasted power of SVR+GN is closer to the original power while forecasted power using the non-linear model is the farthest and the forecasted power using persistence and SVR cannot keep up with the unpredictable cloudy weather.



Fig. 4: Bivariate Hour-ahead Solar PV Power Forecasting on (a) Sunny day, (b) Partly Sunny Day and (c) Overcast Day

To further verify the accuracy of SVR+GN, SVR, persistence and non-linear models, error evaluation parameters like MAPE, MRE, RMSE and MAE were used.

Weather	Error Parameter	SVR+GN	SVR	Persistence	Non-Linear
	MAPE	2.52	3.64	0.55	3.68
Sunny Day	MRE	1.89	2.67	0.40	2.70
~ y = y	RMSE	10.07	12.23	2.08	12.42
	MAE	8.19	11.59	1.75	11.71
	MAPE	5.68	2.58	2.74	2.35
Partly Sunny	MRE	4.05	1.79	1.90	1.62
Day	RMSE	21.16	11.92	16.65	11.73
	MAE	17.57	7.77	8.26	7.02
	MAPE	14.46	15.76	23.11	44.97
Overcast Dav	MRE	5.07	4.59	7.40	15.04
	RMSE	26.57	27.87	44.82	69.36
	MAE	22.0	19.93	32.13	65.27

Tab. 2: Error Parameters for Bivariate Hour-ahead Solar PV Power Forecasting

As shown in Tab. 2, the SVR+GN forecasted solar PV power output with higher accuracy on a sunny day than a partly cloudy and an overcast day in bivariate mode. In terms of MAPE, MRE and MAE, the values indicate that the SVR+GN model successfully achieved an accuracy of 97.48%, 98.11% and 91.81% respectively on a sunny day. The proposed SVR+GN model achieved better accuracy in comparison with SVR and non-linear models. However, the persistence model seemed to work better than the SVR+GN model on that day.

On a partly sunny day, the non-linear model was able to keep the error values at the lowest as compared to the SVR+GN, SVR and persistence models. In terms of MRE, the non-linear model achieved an accuracy of 98.38% whereas SVR+GN was able to forecast power output with 95.95% accuracy.

SVR+GN model achieved the best results on an overcast day. Generally, this type of weather makes it difficult for forecasting models to perform with higher accuracy. Nevertheless, the proposed model effectively achieved higher accuracy than the SVR, non-linear and persistence models. To calculate RMSE, the difference between original and forecasted solar PV power values is squared and hence, it has high values when the forecasted value is not in a near range of the original power output value. On an overcast day, SVR+GN was able to keep RMSE value half of that of the persistence model and one-third of that of the non-linear model. Therefore, it is proved that the SVR+GN model provides better forecasting than SVR and non-linear models on a sunny day. Additionally, the proposed model forecasts more accurately than the SVR, non-linear and persistence models on an overcast day in bivariate form.

4.2. Multivariate Mode

The training and testing of the SVR+GN model were executed using temperature and humidity data along with solar irradiance and power output data in multivariate mode.





Fig. 5: Multivariate (with Temperature) Hour-ahead Solar PV Power Forecasting on (a) Sunny day, (b) Partly Sunny Day and (c) Overcast Day

Fig. 5 shows the solar PV power forecasting graphs in multivariate mode using temperature data. This introduction

of new data in the training and testing phase had significantly affected the forecasting accuracy of the SVR+GN model. It can be seen that the performance of the SVR+GN model was lower than that of the other three models on a sunny day. However, the SVR+GN model was able to recover its performance on a partly sunny and overcast day. Graphs in Fig. 5(b) and Fig. 5(c) depict the forecasted power by the SVR+GN model was very close to the original power values as compared to the forecasted power by SVR, persistence and non-linear models.

Further, in the multivariate mode, the humidity data was also introduced along with solar insolation, power output and temperature data. The performance of all the models against the original power output of the UQ's solar PV plant is shown in Fig. 6.



Fig. 6: Multivariate (with Temperature and Humidity) Hour-ahead Solar PV Power Forecasting on (a) Sunny day, (b) Partly Sunny Day and (c) Overcast Day

On a sunny day, the performance of the SVR+GN model was lower, however again it was able to perform better on a partly sunny and overcast day. Changes in the performance of SVR+GN and SVR models depending on the training data are evidently visible in Fig. 4, Fig. 5 and Fig. 6.

Generally, the solar PV power output is directly dependent on the solar insolation received by that PV. Though, temperature and humidity affect the solar PV power output; temperature and humidity does not affect the solar PV power output to a great extent. Solar insolation plays the main part in the solar PV power output. Interestingly, the performance of the SVR+GN model degraded as the data on which the solar PV output is less dependable like temperature and humidity data was added. However, the performance of the simple SVR model got better as the input data for the forecasting model were extended. Providing more data in the training phase for the SVR model did improve the accuracy of the forecasting. Whereas, the proposed SVR+GN model performed better and provided better accuracy in its bivariate form where no additional data or long data were needed in the training and testing phase.

Error Parameters for multivariate hour-ahead solar PV power forecasting are given in Tab. 3. The error parameters

for SVR+GN and simple SVR models were calculated separately for temperature and temperature+humidity data. Notably, the values for MAPE on a sunny day for SVR+GN were increased by more than three times when the temperature data was added in training and testing the model. Whereas, MAPE for the SVR model with both temperature and temperature+humidity data were lowered than that in bivariate mode.

	T.	SVR	+GN	SV	/R		N
Weather	Parameter	Temperature	Temperature +Humidity	Temperature	Temperature +Humidity	Persistence	Non- Linear
	MAPE	8.03	7.17	3.07	3.02	0.55	3.68
Sunny	MRE	5.94	5.28	2.25	2.21	0.40	2.70
Day	RMSE	25.97	23.27	10.49	10.41	2.08	12.42
	MAE	25.78	22.93	9.76	9.59	1.75	11.71
	MAPE	2.45	2.47	2.35	2.48	2.74	2.35
Partly Sunny	MRE	1.68	1.71	1.62	1.71	1.90	1.62
Day	RMSE	11.80	12.60	11.69	11.50	16.65	11.73
	MAE	7.30	7.35	7.02	7.43	8.26	7.02
	MAPE	21.17	29.05	17.84	21.43	23.11	44.97
Overcast Day	MRE	7.22	9.76	5.28	5.87	7.40	15.04
	RMSE	35.11	46.13	29.98	31.02	44.82	69.36
	MAE	31.35	42.34	22.90	25.47	32.13	65.27

Tab. 3: Error Parameters for Multivariate Hour-ahead Solar PV Power Forecasting

The SVR+GN model outperformed the persistence and non-linear model on a partly sunny day in terms of MAPE, MRE, RMSE and MAE. Moreover, if the proposed model is compared with the simple SVR model, their error values were mostly similar with a negligible difference.

On the erratic overcast day, all these models seemed to fail in the performance and their accuracy was highly affected as evident in their high values for all error parameters.

5. Conclusion

Accurate solar PV power forecasting is essential for the effective integration and participation of large-scale solar PV plants in the electricity markets. The hour-ahead forecasting is mainly used for market clearing and precise power dispatch. For this purpose, a robust forecasting model is required which can provide accurate solar PV power forecasting in different weather conditions which requires less training data, is quickly learning and computationally simple.

The SVR+GN model presented in this paper has proven to be computationally simple, quick learning and performs well even with less training data. The performance of this model was tested in both bivariate and multivariate modes. The proposed model was compared with simple SVR, non-linear and persistence models and the SVR+GN model outperformed simple SVR and non-linear models. In the multivariate mode, the SVR+GN model had higher accuracy than all other models it was compared with on a partly sunny day. This model proved its robustness with lower error parameters like MAPE, MAE, MRSE and MRE. Moreover, the SVR+GN model gave the best performance on the unreliable overcast day when all models failed to provide accurate forecasting.

To further improve the accuracy of power forecasting, the SVR and other machine learning models need more data to train. In contrast, the presented SVR+GN model performed much better in simple bivariate form. This

model has even further potential to improve its forecasting accuracy by monitoring the residual between actual and trained data.

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Evaluation of Technical Feasibility and Financial Attractiveness of a 1MWp Solar Photovoltaic Generator on Ground and Building Rooftops at the Federal University of Santa Catarina – Brazil

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Abstract

This work aims to evaluate and to compare the technical and financial feasibility of two separate 1 MWp photovoltaic (PV) systems that would be installed in different locations on the Universidade Federal de Santa Catarina (UFSC) campus, located in Florianópolis, Brazil. The PV systems would be connected to the consumer unit (CU) Fazenda da Ressacada (fully ground mounted) and CU Cidade Universitária (fully rooftop mounted) with compensation of surplus energy in medium and low voltage CU's. It is observed that the PV system connected to the CU Cidade Universitária would produce around 1.312 MWh/year, and the PV system connected on the ground of the CU Fazenda da Ressacada would produce 1.460 MWh/year. Considering all the aspects of legal restrictions and financial aspects of the installation, even with a lower energy production, the rooftop PV generator presents itself as a very attractive option due to the potential of self-consumption.

Keywords: Solar energy, photovoltaic solar generation, technical and financial feasibility of photovoltaic systems

1. Introduction

Electricity consumption has become indispensable. Its supply must be safe and sustainable. The obvious choice for a clean energy source, which is abundant and inexhaustible, is energy from the sun. With regard to energy consumption, it is known that buildings represent a very high percentage of electricity consumption compared to other economic sectors (GUL and PATIDAR, 2014). Buildings and the construction industry combined account for more than a third of the world's total energy consumption, with buildings contributing with approximately 28% of all energy-related CO₂ emissions in the world in 2018 (IEA, 2019). Commercial buildings, mainly offices and universities, are among those with the highest consumption of electricity. In addition, in the case of photovoltaic energy generation, electricity produced by means of photovoltaic modules can be made both in large utility-scale power plants and by decentralized, urban rooftop PV systems (SMETS et al., 2015).

University campuses are the ideal places for the deployment of photovoltaic solar generation, because of the nature of the activities taking place; there is a great coincidence between solar availability and the demand for electricity, since the air conditioner is the equipment that presents the highest consumption in these buildings. The adoption of solar PV energy in university campuses, due to the concomitance between generation and consumption, presents itself as a very interesting strategy to reduce electricity consumption.

The concept of sustainable university can be defined as a higher education institution that involves and promotes the minimization of environmental, economic and social effects generated by the use of its resources (VELAZQUEZ et al., 2006). Sedlacek (2013) emphasizes that universities play a fundamental role in sustainable development at the regional level. A greater concern with energy sustainability on university campuses has emerged since the publication of the European Directive on Energy Performance in Buildings (EPBD) (JANSSEN, 2004).

Kolokotsa et al. (2016) state that, with regard to physical space, population and the various types of activities carried out on campuses, universities can be considered as mini-cities. Alshuwaikhat and Abubakar (2008) show that the energy and environmental impacts caused by universities through their teaching and research activities and operations can be considerably reduced by using efficient choices of organizational and

managerial measures.

In Brazil, a net-meetering system is adopted, in the form of credits to be used by the consumer unit in subsequent billing periods. According to Normative Resolution No. 482 (ANEEL, 2012), for CUs participating in the energy credit compensation system, compensation must occur firstly at the same time-of-use period where the generation took place. Any remaining credits can then be used at different time-of-use periods.

According to the publication of the *Conselho Nacional de Política Fazendária* (CONFAZ, 2015), the Goods and Services Circulation Tax (ICMS) Agreement 16, of 4/22/2015, authorized the federated units to grant exemption in internal operations related to the circulation of electricity. Thus, the states that adhered to the ICMS Agreement 16/2015 are allowed to grant exemption from the ICMS levied on electricity injected into the utility's grid by the consumer. In the state of Santa Catarina, Decree No. 233 of August 30, 2019 was issued, which introduced attributions relating to the circulation of electricity subject to billing under the credit compensation system, applying to consumer units with installed generation capacity of less than or equal to 1 MW.

Therefore, for the study of credit compensation arising from the energy injected into the utility grid, in the composition of the compensation tariff, the ICMS levy on the generated energy credit will not be accounted for. An important issue addressed in ANEEL Normative Resolution No. 482 (ANEEL, 2012) is the limitation of the installed PV power capacity. Any installed power plant must be limited by the power made available to the consumer unit by the utility, which is the contracted power demand. In the case of an increase in installed capacity, an increase in contracted demand must be requested.

2. Methodology

This work aims to analyze the technical and financial feasibility of installing a 1 MWp PV generator in two CUs owned by UFSC located in Florianópolis, Santa Catarina, Brazil. UFSC has 82 consumer units, of which 23 are connected to medium voltage (MT) and 59 to low voltage (LV). For this study, the CUs Cidade Universitária and Fazenda da Ressacada were chosen. These CUs are powered by 13.8 kV distribution feeders. UFSC contracts its electricity from the local utility grid.

In order to evaluate the solar photovoltaic generation of a ground-mounted system installed at the CU Fazenda da Ressacada II and a roof-mounted PV systems added to the CU Cidade Universitária, the PVSyst software was used (MERMOUD, 2017). The values for standardized losses that were entered in the program are shown in Table 1.

ſ	Ohmic Losses	Module efficiency Loss	Mismatch Losses	Soiling Loss	Unavailability of the system	LID Losses
	1.50%	-0.80%	1.00%	3.00%	0%	1.30%

Tab. 1 - Standardized losses adopted in the PVSyst software

2.1. CU- Cidade Universitária

CU Cidade Universitária covers several buildings in the UFSC's main campus. These buildings allow the installation of PV modules on their rooftops. For the installation of the 1 MWp PV system in this CU, the rooftops of buildings that present better positioning and higher solar incidence were selected.

Figure 1 shows the three-dimensional model used in the simulations of the buildings that are part of the UC Cidade Universitária. Figure 1 shows the Environmental Engineering building as an example.



Fig. 1 – Adapted three-dimensional model of the Environmental Engineering building

2.2. CU - Fazenda da Ressacada

Figure 2 shows the three-dimensional model used in the simulation of the CU Fazenda da Ressacada. All aerial images are facing north and are not to scale.



Fig.2 - Simulated system and its location on the ground

In the coverage area of CU Fazenda da Ressacada, in addition to some buildings, there are several areas for different academic activities and areas still without occupation, suitable to install the 1 MWp PV ground-mounted system. For the installation of the 1 MWp PV generator in this CU, only areas that are currently not occupied were selected.

For both CUs, the installed power of the photovoltaic system is equivalent to the sum of the output power of all inverters (990 kVA).

2.3. Technical indicators

To assess the effective production of the PV system for each set of buildings, on a monthly and annual basis, the global performance (Performance Ratio), the productivity and the capacity factor were calculated.

Equation 1 presents the global performance (PR) of the system, where i is the specified time interval, P is the installed power, $E_i^{generated}$ is the energy generated by the PV system in the specified time interval (obtained via PVSyst software), expressed in kWh, I^{ref} is the reference irradiance (1,000 W/m²) and Irr_i is the solar irradiation in the specified time interval (obtained via BRSN data), expressed in kWh/m.

$$PR_i = (E_i^{generated}, I^{ref})/(P.Irr_i)$$
 (eq. 1)

Equation 2 presents the productivity (Yield) of the system, where Y_i is the yield in the specified time interval i, P is the installed power, expressed in kW; $E_i^{generated}$ is the energy generated by the PV system in the specified time interval, expressed in kWh (obtained via PVSyst software).

$$Y_i = E_i^{gerada} / P \qquad (eq. 2)$$

Equation 3 presents the system capacity factor, where FC_i is the capacity factor in the specified time interval i, P is the installed power of the plant, expressed in kW; $E_i^{generated}$ is the energy generated by the PV system in the specified time interval, expressed in kWh (obtained via PVSyst software).

$$FC_i = \frac{E_i^{generated}}{P*i} \qquad (eq. 3)$$

2.4. Economic indicators

For both PV installations, the financial analysis takes into account the equipment costs including delivery fees to the end customer. A service life span of 25 and 15 years for the photovoltaic modules andfor the inverters, respectively, were adopted. Replacement of these equipments was counted for at the end of their service life. The exchange rate for the transformation of Brazilian real to US dollar used was 5.56.

The energy consumption of the CUs was calculated based on their respective energy bills from January to December 2019. The cost of the rooftop PV system considered was 3.56 R\$/Wp (GREENER, 2020) and 3.97 R\$/Wp for ground-mounted systems (GREENER, 2020). A drop in the annual efficiency of the PV modules of 0.5% and an annual operating and maintenance rate of 1% were considered.

For both CUs, the analysis of the financial attractiveness of the return on investment was carried out, for various interest rates, by obtaining financial indicators, such as Net Present Value - NPV, discounted payback, Internal Rate of Return - IRR and Levelized Cost of Energy - LCOE. In these studies, inflation was not considered.

The LCOE was calculated, according to equation 4, where I is the initial investment, N is the equipment's lifetime, i is the minimum attractive rate of return, A is the maintenance cost and M the generated energy.

$$LCOE = \frac{I + \sum_{t=1}^{n} \frac{At}{(1+t)t}}{\sum_{t=1}^{n} \frac{Mt}{(1+t)t}} \qquad (eq. 4)$$

Net present value was calculated from equation 5, where NPV = Net Present Value, I = Initial investment, FCj = Revenue from year j, i = Annual interest rate used and n = Equipment useful life.

$$VPL = \sum_{j=n}^{n} \frac{FCj}{(1+i)^n} - I \qquad (eq. 5)$$

In both cases, the internal rate of return was calculated from equation 6, where IRR = Internal Rate of Return, i = Annual interest rate used and n = Equipment useful life.

$$-I + \sum_{j=n}^{n} \frac{FC_j}{(1+TIR)^n} = 0$$
 (eq. 6)

3. Results

3.1. Energy generation and consumption

3.1.1. – CU Cidade Universitária

Table 2 shows the inclination, azimuth deviation, performance indicators and the PV generated energy for the buildings that are part of CU Cidade Universitária.

Building	Inclination / Azimuth deviation	System Power (kWp)	N° Modules	PR (%)	Yf (MWh/ kWp/ year)	Capacity Factor	Energy (MWh/ Year)
University library	10/85 e 10/-95	549	1.526	0.765	1.22	13.92%	669.80
Health Sciences Center	10/-45 e 10/135 e 10/45 e 10/-135	105	292	0.77	1.23	14.04%	129.1
Control and Automation Engineering	10/17 e 10/-163 e 10/- 73 e 10/107	101	280	0.765	1.21	13.82%	122.34
Mechanical Engineering	10/175 e 10/-5	101	280	0.727	1.16	13.18%	116.62
Production engineering	10/-4 e 10/175	120	332	0.769	1.23	13.98%	150.07
Environmental Engineering	10/176 e 10/-5 e 10/- 118 e 10/62	102	282	0.767	1.23	13.94%	124.63
TOTAL	-	1.081	3.000	0.762	1.22	13.81%	1,312.59

Tab. 2 - Simulated systems characteristics - CU Cidade Universitária

It is observed that the PV systems have very similar PR, yield and capacity factor (respectively 0.77, 1.23 MWh/kWp/year and 14%), except for those installed in the Mechanical Engineering building (0.73, 1 .16 MWh/kWp/year, 13%). This difference is due to the greater losses due to shading verified in the latter.

Figure 3 shows the monthly evolution of the solar irradiation and the generated PV energy of the system to be connected at CU Cidade Universitária.



Fig. 3 - Monthly evolution of the PV generation and solar irradiation - CU Cidade Universitária

From Figure 3, it can be observed the seasonality of the PV generation. Less energy was generated during the winter months, as oppose to the summer months, given the higher incidence of solar irradiation.

Figure 4 shows the energy consumption during at peak and off-peak hours and solar PV generation at CU Cidade Universitária.



Fig. 4 - Energy consumption and solar PV generation at CU Cidade Universitária

Energy consumption at CU Cidade Universitária was higher during off-peak hours. It is during this timeframe that most classes are held, as they take place during business hours. In addition, during daylight hours, consumption in order to meet air conditioning demands is higher, characterizing a seasonality in energy consumption, consuming more in the months with higher temperature.

This work admits that all photovoltaic generation will be generated and consumed/compensated at off peak timeframe at CU Cidade Universitária. Therefore, the savings obtained by the insertion of PV generation will come from the energy itself, which will no longer be purchased from the grid, multiplied by the consumption tariff.

3.1.2. - CU Fazenda da Ressacada

For the buildings that are part of CU Fazenda da Ressacada II, Table 3 shows the inclination, azimuth deviation, performance indicators and the PV generated energy.

Consumer Unit	Inclination / Azimuth deviation	System Power (kWp)	N° Module s	PR (%)	Yf (MWh/ kWp/ year)	Capacity Factor	Energy (MWh/ Year)
Fazenda Ressacada	22/0	1,081	3,000	0.789	1,352	15.41%	1,460

Tab. 3- Simulated systems characteristics - CU Fazenda da Ressacada II

In this case, the results show a PR of 0.79, yield of 1.35 MWh/kWp/year and capacity factor of approximately

15%.

Figure 5 shows the monthly evolution of the solar irradiation and the generated PV energy of the system to be connected at CU Fazenda da Ressacada II.



Fig. 5 - Monthly evolution of the PV generation and solar irradiation - CU Fazenda da Ressacada II

It is observed that the photovoltaic generation at the UC Fazenda da Ressacada II followed the solar irradiation curve for its location. The seasonality of the generation is observed, producing less during winter months when compared to the summer months, given the higher incidence of solar irradiation.

Figure 6 shows the energy consumption during at peak and off-peak hours and solar PV generation at CU Fazenda da Ressacada II.



Fig. 6 - Energy consumption and solar PV generation at CU Fazenda da Ressacada II

Energy consumption at the UC Fazenda da Ressacada II was higher during off-peak hours. During this time, most classes are held, as they take place during business hours.

Taking into account the low consumption of the CU Fazenda da Ressacada II, the active energy generated in this location, in addition to reducing the off-peak consumption, will have its surplus injected into the utility grid. As a result, energy credits will be generated, which can be used to discount the consumption of CU owned by UFSC through remote self-consumption.

3.1.3. - Energy comparison

Figure 7 shows, for CU Cidade Universitária and CU Fazenda da Ressacada, the monthly evolution of energy that would be generated by the PV-generation of 1 MWp.



Fig. 7 – Monthly evolution of photovoltaic generation

The results show that the PV generation installed on the roofs of the buildings located at the CU Cidade Universitária, with different tilts and orientations, would produce about 1,312 MWh/year, while the PV generation of 1 MWp, installed on the ground of the CU Fazenda da Ressacada with orientation to the north, tilted at the local latitude angle (27.685° South; 48.544° West), would produce approximately 1,460 MWh/year. In addition, the system of the CU Fazenda da Ressacada II presents less shading, as there are no trees and buildings in the vicinity of the simulated system.

3.2. Financial attractiveness

3.2.1. – CU Cidade Universitária

Table 4 presents the systems installed power, cost per W of rooftop mounted systems (GREENER, 2020) and total cost.

Tab. 4	Installed	power a	and cos	st of PV	installation	at CU	Cidade	Universitária
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Installed Power (kWp)	Cost (US\$/Wp)	Total (US\$)
1,081	0.64	692,151.08

The contracted power demand at the CU is 4,500 kW, so there will not be an increase in contracted values. Due to the uncertainty of the demand reduction value provided by the aggregation of solar PV energy to the CU, the expenses avoided by the reduction in demand (contracted and measured) were not considered in the calculations of the financial attractiveness.

Table 5 shows the PV generation and the expenses that would be avoided by inserting the photovoltaic system at CU Cidade Universitária.

Tab.	5 - Summarv	table of PV	generation an	d avoided e	expenses - CU	Cidade V	Universitária
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Month	PV Generation (kWh)	PV Generation (kWh)Off-peak tariff (US\$/kWh)Cost avoided with energy consumption 		Operation and Maintenance Costs (US\$)	Total benefits generated (US\$)	
Jan/19	152,640	0.0989	15,073.06	576.79	14,529.11	
Feb/19	130,780	0.0953	12,355.09	576.79	11,808.00	
Mar/19	125,480	0.0881	11,197.06	576.79	10,639.05	
Apr/19	94,980	0.0863	8,314.97	576.79	7,746.59	
May/19	78,690	0.0881	6,950.96	576.79	6,369.17	
Jun/19	64,370	0.0917	6,014.54	576.79	5,430.04	
Jul/19	70,480	0.0971	6,970.32	576.79	6,390.77	
Aug/19	88,270	0.0971	8,632.04	576.79	8,054.77	
Sep/19	91,020	0.0791	7,223.29	576.79	6,661.31	
Oct/19	116,440	0.0755	8,948.14	576.79	8,391.13	
Nov/19	143,550	0.0737	10,639.82	576.79	10,096.36	
Dec/19	155,890	0.0755	11,664.27	576.79	11,128.37	
Total	1,312,590	-	113,983.57	6,921.50	107,244.67	

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For CU Cidade Universitária and for the analyzed period, the monetary benefits (avoided expenses) due to the installation of the PV system would be US\$ 107,244.67.

3.2.2. – CU Fazenda da Ressacada

Table 6 presents the systems installed power, cost per W of ground mounted systems (GREENER, 2020) and total cost.

Tab. 6- Installed power and cost of PV installation at CU Fazenda da Ressacada

Installed Power (kWp)	Cost (US\$/Wp)	Total (US\$)
1,081	0.71	771,865.11

As the contracted demand of CU Fazenda da Ressacada is less than 1 MWp, after the installation of the 1 MWp PV generator, it would be necessary to increase the contracted demand of this CU to 1 MW. Table 7 shows the monthly evolution of electricity expenses due to the increase in contracted power demand.

Tab. 7- Monthly evolution of expenses due to the increase in contracted demand - CU Fazenda da Ressacada

Month	Contracted demand (kW)	Charged demand (kW)	New Power Demand (kW)	Increase in contracted demand (kW)	Power demand tariff (US\$/kW)	Additional expenses due to Contr. Demand (US\$)
Jan/19	100	100	990	890	3.33	2,961.17
Feb/19	50	60.92	990	940	3.18	2,957.32
Mar/19	50	50	990	940	3.01	2,826.17
Apr/19	50	50	990	940	2.95	2,772.66
May/19	50	50	990	940	2.97	2,797.65
Jun/19	50	50	990	940	3.15	2,959.29
Jul/19	50	50	990	940	3.33	3,132.24
Aug/19	50	50	990	940	3.39	3,186.62
Sep/19	50	50	990	940	3.37	3,169.51
Oct/19	50	50	990	940	3.26	3,069.19
Nov/19	50	50	990	940	3.15	2,960.22
Dec/19	50	50	990	940	3.18	2,988.36
Total	-	-	-	-	-	35,780.42

For the period analyzed, it is observed that the expenses related to the increase in contracted power demand would be US\$ 35,780.42.

Table 8 shows the monthly evolution of the avoided expense due to the PV generation that would be inserted in the CU Fazenda da Ressacada II.

Month	Off Peak Consumption (kWh)	Off peak tariff (US\$/kWh)	Peak Consumption (kWh)	Peak energy credits compensation tariff (US\$/kWh)	Total benefits generated from avoided expenses (US\$)
Jan/19	17,592.40	0.0989	1,847.77	0.28	2,252.49
Feb/19	18,479.38	0.0953	1,807.06	0.27	2,243.87
Mar/19	16,532.32	0.0881	1,979.20	0.25	1,960.01
Apr/19	18,591.27	0.0863	2,147.16	0.25	2,141.80
May/19	18,950.34	0.0881	2,398.87	0.25	2,274.47
Jun/19	20,284.48	0.0917	2,308.37	0.26	2,471.00
Jul/19	20,420.45	0.0971	2,569.00	0.28	2,696.37
Aug/19	20,738.25	0.0971	2,612.06	0.27	2,720.17
Sep/19	19,656.33	0.0791	2,542.84	0.26	2,211.98
Oct/19	13,144.00	0.0755	1,818.00	0.25	1,449.65
Nov/19	18,202.63	0.0737	2,288.60	0.24	1,899.94
Dec/19	16,494.46	0.0755	2,039.18	0.24	1,746.87
Total	219,086.31	-	26,358.11	-	26,068.62

Tab. 8- Total benefits generated - CU Fazenda da Ressacada II

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It is observed that, for the analyzed period, the total avoided expenses provided by PV generation would be US\$ 26,068.62.

The analysis of the total benefits generated from the injection of PV energy into the utility grid took into account the generation of credits for compensation in medium and low voltage CUs. For the different voltage classes in which the CUs are serviced, energy tariffs have different values.

Table 9 shows the monthly values for the generation of energy credits arising from the energy injected into the grid by the system simulated at the CU Fazenda da Ressacada II. Table 9 also presents the respective tariffs applied to the energy credits for compensation in medium and low voltage.

 Tab. 9- Monthly evolution of energy credits that would be generated by CU Fazenda da Ressacada II and respective financial benefits arising from energy credits for compensation in CUs powered by low and medium voltage

Month	PV Generation (kWh)	Energy injected into the grid (kWh)	Compensation tariff for LV CU (US\$/kWh)	Benefits arising from energy credits at LV CUs (US\$)	Compensation tariff for MV CU (US\$/kWh)	Benefits arising from energy credits at MV CUs (US\$)
Jan/19	149,300	128,774.63	0.13	16,170.59	0.094	12,087.345
Feb/19	135,800	114,452.27	0.12	13,794.74	0.090	10,289.347
Mar/19	140,600	120,926.09	0.11	13,834.28	0.085	10,304.906
Apr/19	115,100	93,100.53	0.11	10,466.46	0.083	7,782.750
May/19	107,100	84,341.92	0.11	9,572.98	0.084	7,111.354
Jun/19	88,400	64,451.44	0.12	7,698.55	0.089	5,736.176
Jul/19	95,100	70,601.77	0.13	8,878.38	0.094	6,639.709
Aug/19	110,900	85,658.19	0.11	9,623.47	0.078	6,741.079
Sep/19	103,000	78,959.46	0.11	8,458.60	0.074	5,901.014
Oct/19	121,800	105,521.57	0.10	10,957.07	0.072	7,641.365
Nov/19	141,800	119,651.51	0.10	12,038.47	0.070	8,364.254
Dec/19	151,200	131,189.71	0.10	13,287.65	0.070	9,261.092
Total	1,460,100	1,197,629.08	-	134,781.25	-	97,860.39

For the analyzed period, the results show that the annual benefit provided by the energy credits generated in the UC Fazenda da Ressacada II would be US\$ 134,781.25, considering that all credits were used in the low voltage CU, and that US\$ 97,860.39 were used for compensation in medium voltage CUs.

Table 9 shows the monthly evolution of avoided expenses, the increase in expenses due to the new contracted power demand, expenses with operation and maintenance of the PV system and the benefits due to the usage of energy credits in the CU Fazenda da Ressacada.
Month	Total benefits generated from avoided expenses (US\$)	Benefits arising from energy credits at MV CUs (US\$)	Benefits arising from energy credits at LV CUs (US\$)	Additional expenses due to Contr. Demand (US\$)	O&M Costs (US\$)	Total resulting benefits (compensat ion MV) (US\$)	Total resulting benefits (compensati on LV) (US\$)
Jan/19	2,252.49	12,087.345	16,170.59	2,961.17	576.79	10,735.442	14,818.691
Feb/19	2,243.87	10,289.347	13,794.74	2,957.32	576.79	8,932.678	12,438.068
Mar/19	1,960.01	10,304.906	13,834.28	2,826.17	576.79	8,795.529	12,324.905
Apr/19	2,141.80	7,782.750	10,466.46	2,772.66	576.79	6,508.664	9,192.371
May/19	2,274.47	7,111.354	9,572.98	2,797.65	576.79	5,944.950	8,406.572
Jun/19	2,471.00	5,736.176	7,698.55	2,959.29	576.79	4,604.656	6,567.032
Jul/19	2,696.37	6,639.709	8,878.38	3,132.24	576.79	5,560.617	7,799.291
Aug/19	2,720.17	6,741.079	9,623.47	3,186.62	576.79	5,631.408	8,513.802
Sep/19	2,211.98	5,901.014	8,458.60	3,169.51	576.79	4,300.268	6,857.853
Oct/19	1,449.65	7,641.365	10,957.07	3,069.19	576.79	5,378.604	8,694.308
Nov/19	1,899.94	8,364.254	12,038.47	2,960.22	576.79	6,660.743	10,334.964
Dec/19	1,746.87	9,261.092	13,287.65	2,988.36	576.79	7,376.381	11,402.942
Total	26,068.62	97,860.39	134,781.25	35,780.42	6,921	80,429.94	117,350.80

Tab. 9- Avoided expenses, increased expenses due to the new contracted demand and benefits from the insertion of PV generation in the UC Fazenda da Ressacada

It is observed that the total benefit generated is the result of the revenues due to the avoided energy expenses during off-peak hours, added to the credits generated resulting from the injection of energy into the grid, subtracted by the system maintenance cost and the additional contracted power demand costs.

The total annual benefits generated by the PV system inserted in the UC Fazenda da Ressacada would be US\$ 117,350.80 (for credits written off in LV CUs) and US\$ 80,429.94 (for credits written off in MV CUs).

3.2.3. - Comparison of financial attractiveness

Table 10 shows, for the 1 MWp PV generator simulated for both CUs, the evolution of NPV, payback and IRR for different Minimum Attractive Rate of Return (MARR).

	Cidade Universitária			Fazenda da Ressacada (Energy credit compensation at MV CUs)			Fazenda da Ressacada (Energy credit compensation at LV CUs)		
MARR	NDV (US\$)	Payback	IRR	IRR NDV (LISC) Payt		IRR	NDV (US\$)	Payback	IRR
(%)	NF V (US\$)	(years)	(%) (0.53) (years) (%)		$NPV(US\phi)$	(years)	(%)		
2	1,129,340	7.1		585,156	10.5		1,232,719	7.2	
3	931,098	7.4		451,053	11.2		1,026,559	7.5	
4	762,557	7.8		336,980	12.1		851,210	7.9	
5	618,479	8.2		239,375	15.6		701,224	8.3	
6	494,649	8.6	12%	155,381	17.2	8%	572,218	8.8	13%
7	387,655	9.2		82,692	19.4		460,652	9.3	
8	294,726	9.8		19,439	23.1		363,651	9.9	
9	213,602	10.5		-	-]	278,872	10.7	
10	142,431	11.4		-	-]	204,400	11.7	

Tab. 10: Evolution of NPV, Payback and IRR

It is observed that a PV system of 1 MWp inserted in the CU Fazenda da Ressacada II with compensation of excess PV energy in UFSC's CUs fed in LV presents a greater financial attractiveness than if compensated in CUs fed in MT. This significant difference is related to its energy credit compensation. As the monomial low voltage energy tariff is higher than the binomial tariff during off-peak hours in medium voltage, it would be more attractive to use these energy credits in units belonging to UFSC powered at low voltage.

For the CU Cidade Universitária, the financial attractiveness would be a close second overall. However, if the CU Fazenda da Ressacada did not present any off-peak energy consumption from its loads, its NPV would be greater, increasing the difference.

4. Conclusion

This study aimed to compare technically and financially, through simulations, two PV installations with a capacity of 1 MWp to be connected in two Consumer Units (Cidade Universitária and Fazenda Ressacada II), both owned by the Universidade Federal de Santa Catarina.

For the insertion of PV generation in the UC Fazenda da Ressacada II, the LCOE was US\$ 37.54/MWh (with compensation of the excess PV energy at the CUs fed in low voltage). The results show the feasibility of the project, considering that the LCOE value is lower than the values charged by the utility, both for medium and low voltage rates. Finally, after analyzing the costs involved in the installation of the PV system, together with the costs of contracting a higher power demand and the fact that the compensation tariff for credit generation is different for CU fed in MV and LV, the compensation of excess energy in medium voltage CUs becomes less attractive when compared to compensation in low voltage CUs.

For the insertion of the PV generation in the CU Cidade Universitária, the results showed an LCOE of US\$ 30.16 /MWh. In this case, a comparison between LCOE with the average value of the utility's tariff (87.73 US\$/MWh), shows that photovoltaic energy is cheaper than energy purchased from the grid.

It is observed that the installation of a 1 MWp PV generator at CU Fazenda da Ressacada with compensation for surplus energy in the low voltage CU's grid presents financial attractiveness very close to the adoption of the same 1 MWp PV generator at the Cidade Universitária CU. However, although there is available land area for the implementation of the PV system, when the cost of availability of the land is considered, which would no longer be used for any other academic purpose, the attractiveness of the project to insert PV generation in the CU Fazenda da Ressacada II would be smaller than the insertion of the PV generation on the roofs of buildings that are part of CU Cidade Universitária.

Furthermore, when applied to the CU Cidade Universitária, a maximization of self-consumption would occur, making the financial attractiveness independent from future Brazilian regulatory changes regarding energy injected into the grid. Therefore, from the point of view of UFSC, the installation of the PV on the roofs of buildings whose electrical systems are connected to the CU Cidade Universitária is very attractive.

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G-04. Energy System Studies (Operation and Planning)

Characterization of Changes in the Soiling Properties and Deposition Rates Because of Groundworks Near a PV Plant in the Atacama Desert.

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Abstract

Solar Plants expansions, site upgrades, and other types of groundworks can affect solar plants by making the soil less compact and more prone to increase of airborne dust in windy events. This causes the soiling rate of photovoltaic panels to rise significantly compared to normal operating conditions. The aim of the paper is to generate information that will help operators and companies make the right decisions in PV plant maintenance plans and in the execution of works to reduce the impact of earthworks on plant performance and maintenance costs. This paper presents the results of a study on the impact of earthworks on soiling properties of PV plants. The methodology is based on the comparison of the soiling rate and its physicochemical and morphological properties before, during and after the groundworks. In addition, the duration of these changes over time after the completion of the earthworks in the area was analysed. The results show that before the works, quartz was the predominant material, which was displaced by gypsum during the works, then at the end of the study, after one year, the site returns to its original composition before the disturbance. Another effect observed is the change in the size of the deposited material, which before the works was dominated by fine material smaller than 10 μ m, while during the works most of the particles were between 20 and 30 μ m and later returned to their size of 10 μ m. Measurements of the deposited dust show that it takes three months (after completion of the works) to return to pre-works contamination levels.

Keywords: Soiling, Dust, Transmittance loss, Photovoltaic, Solar Energy, Operation & Maintenance, Atacama Desert

1. Introduction

Renewable energies (RE), especially solar energy, have a recognized national and international potential for clean energy generation. Internationally, these energy sources have become a real option for the diversification of the energy matrix, dominated for decades by fossil sources based on coal, gas, oil and nuclear energy (Rhodes, 2010). Global warming, citizen empowerment and the modification of public policies have allowed the incorporation of these technologies, through hourly tenders, generating a great industrial and technological development worldwide. The participation in the market of commercial powers such as China has driven a reduction in the prices of materials, equipment and inputs that have favored photovoltaic (PV) technologies, which have shown a higher growth in the last decade, according to the International Energy Agency.

The technological development of PV has grown rapidly to become a profitable and environmentally friendly source of energy and economic activity. In 2020, PV broke the record in installed capacity, reaching a total cumulative capacity of 760,400 MW. In that year alone, the world installed 139,000 MW of new solar PV capacity, with China, the United States, Japan, Germany and India being the main countries contributing to this growth ("Fotovoltaica - La solar fotovoltaica bate récord del mundo - Energías Renovables, el periodismo de las energías limpias.," n.d.). This great development has not only been experienced by these countries, but also by those that are linked to the Photovoltaic Energy Systems Program of the International Energy Agency (IEA PVPS), which consists of 27 nations and concentrates 85% of the global photovoltaic capacity. Countries such as Chile, Australia, Japan, China and the European Union stand out (IEA, 2015).

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Chile leads the incorporation of solar PV energy in Latin America, with a solar market that has grown rapidly in recent years, being the high radiation, temperature, and hours of clear skies of the Atacama Desert a natural laboratory for the development of solar energy worldwide. With a surface area of 105,000 km², values of more than 8 kWh/m² of global radiation (GHI) per day have been recorded (Marzo et al., 2018). Its cloudiness index is 3%, so it has clear sky conditions during most of the year (Escobar et al., 2014). This is mainly due to the influence of the Cordillera de la Costa and the Cordillera de los Andes in their role as a climatic screen in the Atacama Desert (Marzo et al., 2021), preventing oceanic or Amazonian influence in the interior of the desert, which gives this desert a very stable climatology over time. Because of this, the Atacama Desert has a natural potential for solar technologies that has allowed, e.g., the insertion of monofacial and today particularly bifacial photovoltaic technologies. Currently, 1.08 GWp are installed in the Antofagasta region, 0.35 GWp are being tested and 1.4 GWp are under construction, which will reach 2.83 GWp by 2022 (Comisión Nacional de Energía et al., 2022). However, these territorial and radiation advantages are attenuated by local conditions that impose effects such as high UV radiation, temperature and soiling, which affect the performance of PV plants (Cordero et al., 2018; Marzo et al., 2018).

The irruption of PV technology in high radiation desert areas has brought with it a series of challenges related to the operation and maintenance of PV plants, with soiling being one of the major effects to be considered. Soiling is defined as the process by which organic dirt (pollen, bird droppings, silver debris) and inorganic dirt (minerals, salts and sand) accumulate on the surface of the PV module (Conceição et al., 2018a, 2018b; Muñoz-García et al., 2021; Olivares et al., 2020). The presence of deposited material drastically reduces the amount of light reaching the solar cell, generating optical and electrical losses, affecting economically a PV project and making it necessary to look for ways to mitigate its effect (Lorenz et al., 2014; Olivares et al., 2017; Reza et al., 2016). According to a study presented by Ilse et al. (Ilse et al., 2019) in an optimal cleaning scenario, soiling reduces the current global solar energy production by at least 3%-4%, leading to losses of at least 3-5 billion euros per year, which may increase by 4-7 billion euros by 2023. This is a conservative estimate, as it does not consider the optimized costs for residential installations, which represent 29% of the installation.

The exponential growth that has existed in Chile involves the construction and expansion of PV projects. This has generated problems due to the increase of dust resulting from the earthworks, affecting the performance of the modules installed on site and nearby plants. This paper presents the results of a study on the impact of groundworks on the soiling properties of a PV plant located in the Atacama Desert.

2. Materials and Methods

This study was conducted at the Plataforma Solar del Desierto de Atacama (PSDA). This site is an outdoor laboratory for studying and testing different types of solar technologies. The PSDA is operated by the Centro de Desarrollo Energético de Antofagasta (CDEA) belonging to the Universidad de Antofagasta (UA). From the point of view of local environmental characteristics, more specifically in terms of soil and solar resources, the PSDA is a representative site of the conditions found in the area of interest for the solar industry in the Atacama Desert. This is because it is located at 1000 m.a.s.l. in the interior of the Atacama Desert (24.09°S, 69.93°E) between the Cordillera de la Costa and the Cordillera de los Andes. . According to the Köppen climate classification, this site is characterized by a cold arid desert zone (BWk) climate (Peel et al., 2007).

To characterize the impact of nearby earthworks, standard PV glass on the surface of photovoltaic modules were exposed to outdoor conditions during September 2018 and August 2019. Ground movements were conducted between February and March 2019. However, soil mechanics testing and machinery movements were performed in late 2018. A physicochemical characterization, quantification of the mineral composition of the dirt and a morphological analysis (size and shape) were performed. These analyses were carried out during and after the soil movements, completing a whole year of experimentation.

The powder samples collected before, during and after the works were analyzed by X-ray diffraction (XRD), using a Bruker AXS D8 Advance diffractometer in the range of 2-60°, with CuK α radiation ($\lambda = 0.15045$ nm) at 40 kV and 30 mA. These measurements were performed at room temperature. The powder diffraction file (PDF-4) in database format (Kabekkodu et al., 2002) was used to determine the compounds detected by XRD. The TOPAS software was used for their quantification. This program uses the Rietveld method to indicate the amount of each species present in a sample.

To analyze dust particles' size and morphology, an optical microscope was used (Leica DM IRB) to obtain a digital image including a size bar. The images were taken at a 20x magnification and were analyzed with ImageJ software. By analyzing the image with the software, the following parameters for dust particles were

obtained: area (A), perimeter (P), and aspect ratio (Ct). From the area and aspect ratio of the particle, its longest projection (l) was obtained with eq. (1) In addition, a detailed examination of the dust particles was made with scanning electron microscopy (SEM) Joel SEM JSM-6360LV and energy dispersive X-Ray spectroscopy (EDX) for its elemental analysis.

$$l = \sqrt{\frac{4AC_t}{\pi}} \tag{eq. 1}$$

Morphology was studied through the shape factor (A_{shape}). This parameter is defined as the inverse of the particle circularity and is associated with particle complexity. This factor is calculated through eq. 2, where P and A are the perimeter and area of the particle, respectively. A shape factor close to 1 would correspond to a perfect circle. More than 300 particles from each sample were analyzed to ensure representativeness.

$$A_{shape} = \frac{P^2}{4\pi A} \tag{eq. 2}$$

The deposition rate of surface dust density was measured by exposing the samples for periods of one month and recording their mass changes every week. This process was repeated until 12 months of measurements were reached. The campaign consisted of placing the objects in triplicate with a size of $(5 \times 9 \text{ cm}^2)$ on the surface of the photovoltaic modules fixed at an inclination of 20° with north orientation. The method used was gravimetric for mass gain.

Changes in optical properties (such as glass transmittance) caused by soiling were monitored outdoors under natural light at normal incidence. This transmittance was calculated as the ratio of the measured solar irradiance using a Si photocell with dusted PV glass on top of it to the measured solar irradiance using a different Si photocell with no glass on top. In this way, the broadband transmittance of the dust-glass system was determined, being representative for the 300-1200 nm spectral range. These measurements were performed on standard PV glass samples having different surface densities for the study year, a size of 4.7 x 6.5 cm and a thickness of 3.2 mm.

3. Results and Discussion

3.1 Physicochemical characterization

Characterization by X-ray diffraction showed that the material deposited on the photovoltaic modules before the work was composed of: a) Albite (NaSi₃O₈), b) orthoclase (K (AlSi₃O₈)), c) muscovite (KAl₂(AlSi₃O₁₀)(OH)₂), d) quartz (SiO₂) and e) gypsum (CaSO₄ \cdot 2H₂O) as its main components (for more details see (Ferrada et al., 2019). In the diffractograms corresponding to the analysis during and after the works, the same materials were found, as shown in Fig. 1. However, it can be observed that there are differences in the diffractograms of the analyses performed before and after the works compared to the one performed during the works. These differences are related to pronounced gypsum peaks in the sample taken during the work that are not observed in the other two diffractograms. In addition, it can be observed that there is a similarity between the diffractograms of the samples taken before and after the work.

A semi-quantitative analysis by TOPAS showed that the difference observed in the diffractograms is related to the amount of crystalline species deposited on the surface of PV modules. The analysis showed that before the earthworks, quartz was the major compound with a 36% presence. During the work, the presence of quartz decreased to 11% but the amount of gypsum increased to 60%. Finally, for the analyses carried out after the work was completed, quartz again became the main compound with 27%. For these reasons, there is a similarity in the diffractograms performed on the samples before and after the earthworks, since quartz is the major compound. While in the diffractogram during the earthworks, the characteristic peaks of gypsum predominate, this is not the case in the other diffractograms where its presence is 2% and 5%.

Soluble salts, such as gypsum, are abundant in the area where the PSDA is located (Fig. 2.a). Ground presents a hard and compact type of substrate where, in a few decimetres below the surface, a layer of salt is easily distinguishable. This characteristic means that in the presence of water, e.g. light drizzle, these salts appear on the surface of the soil forming a hard white crust (Fig 2. b)(Berger and Cooke, 1997).



Fig. 1: XRD for soiling samples deposited on a string of PV modules at PSDA (pre-earthwork, during earthworks and postearthworks).

These characteristics explain, for example, why dust deposition in the Atacama Desert is lower than in other deserts where the soil is not so compact. When groundworks are performed, the substrate becomes loose and is more easily moved by the wind, causing an increase in the rate of soiling. In the same way, deepening in layers below the surface, salt residues are exposed to the elements, which are deposited on the modules when airborne, leading to an increase in the presence of salts such as gypsum. The increased presence of gypsum changes the shape of the deposited material and further promotes soiling cementation on PV modules. The earthwork caused a disturbance which consisted of an increase in sedimentary material (gypsum). This disturbance tended to equilibrate over time, returning to quartz as the predominant depositional material.



Fig. 2: a) Soil of the PSDA on which the PV plant is installed. b) Formation of crusts caused by artificial watering and the solubilization and subsequent crystallization of gypsum.

3.2. Particle size and morphology

The results of the SEM analysis show that the effect of the ground movements not only produced changes in the amount of crystalline species deposited, but also in the morphology of the material. For the particles analysed before the earthworks there is a predominance of spherical particles with a tendency to generate agglomerates as shown in Fig. 3.a). In addition, the presence of prismatic particles can be observed, but in smaller quantities, as can be identified in Fig. 3.b). Compared to the particles found at the end of the earthworks, defined prismatic particles are found as shown in Fig. 3 c) and d). These defined prismatic particles correspond to the mineral gypsum, which has a monoclinic crystalline structure. The implication of gypsum is its capacity to generate agglomerates as a result of cementation, which produces the so-called "desert rose" (Almohandis, 2002; Ilse et al., 2018). This phenomenon can be better appreciated in Fig. 3 d), in which a well-defined primary particle can be observed surrounded and encapsulated by smaller spherical particles, which have been trapped by the solubilization and recrystallization processes of this salt. For the analysis of the dust samples after the work (Fig. 3. f) and g)), it can be observed that the deposited material again has a predominance of spherical particles, in addition, the presence of clearly defined prismatic particles can be seen, but in smaller quantities.



Fig. 3: Scanning electron microscopy of dust samples deposited on the surface of PV modules. (A) ,(B) Particles pre-earthworks; (C) , (D) Particles during earthworks ; and (E) , (F) particles post-earthworks.

To confirm the results obtained it is necessary to perform morphology tests such as the shape factor. The histogram of the shape factor (A_{shape}) of the deposited material before, during and after the earthworks is shown

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in Fig. 4 left. It can be observed that before and after the earthworks there is a predominance of spherical particles with a frequency of over 40%. For the analyses carried out during the works, the opposite can be observed, the presence of spherical particles is low, less than 5% and 30% for particles far from the unit. These results confirm what was mentioned with the SEM images, showing that the presence of prismatic particles (gypsum) is a product of the earth movements, and that these altered the geology of the site. However, these disturbance will only be during the earthworks.

Particle size was also analysed, and the results are shown in Fig. 4 right. The frequency of fine particles predominates before and after the earthworks. In addition, it is shown that there are no particles larger than 50 μ m for both analyses. In comparison with the analysis of the samples during the work, it is shown that larger particles are frequent, with the size between 20-30 μ m presenting the highest frequency of 28%. In addition, it is observed that particle sizes above 100 μ m were reached, which would be related to the works carried out at the site, as a result of the movements and excavations during the expansion of the PV plant.

The results of the physicochemical and morphological characterization of the deposited material show that the earth movements during the work affect the deposition of the material at the site. The effect is observed in the material chemistry, morphology and size. However, this disturbance that was generated does not last over time; on the contrary, the deposition of the material returns to the state it was in before the work.



Fig. 4 Left: Shape factor pre-earthwork (black), during (red) and post earthworks (blue) at the PSDA. Right: Size particle preearthwork (black), during (red) and post earthworks (blue) at the PSDA

3.3. Soiling deposition rates

Fig. 5 shows the surface dust density over time, during a 12-month exposure period. The glass samples were exposed to outdoor conditions in different one-month measurement campaigns. During each campaign, glass samples were collected each week to evaluate changes in their weight, until the period of exposure was completed. It can be observed that as exposure times increase, the density of cemented dust increases. It can be observed that there is a normality (months #1, #2 and #3), where it is shown that surface dust density does not exceed 0.05 mg cm⁻², with a temporal pattern that suggests an asymptotic behavior, at least in some cases. The disturbance of the works is shown during months #4 and #5, as the amount of cemented material in the samples increased dramatically to values of 0.65 mg cm⁻², i.e., 13 times larger or more than what was obtained during the months prior to the earthworks. During months #6, #7 and #8, the amount of cemented powder decreased progressively. This closely follows the construction activity, which ended in the middle of the 5th month, in which dirt levels clearly decreased and stabilized at their pre-work values. For the last four months of the measurement year, a similar behavior in deposition levels to the first three months can be observed. These values are related to the results of the physicochemical characterization, in which it is observed that the site affected by the works will tend to return to its initial state before the disturbance. In addition, month 11 shows the positive effect of the rain, which helped to reduce the amount of dust deposited, but its effect only allows to return to a density value similar

to that of three weeks of exposure.



Fig. 5: Surface dust density of the samples over the 12 months of outdoor exposure. A slight increase in the deposited dust is observed as exposure time increases. This increase in the amount of deposited soiling occurs when earthworks begin. The vertical dotted lines delimit the period of earthworks for the installation of the nearby photovoltaic plant.

3.4 Effects of soiling

Fig. 6 left shows the measured transmittance of the photovoltaic glass samples exposed to the outdoor conditions in the PSDA. The dust density on the surface of the exposed glass reached 0.66 mg cm⁻². This value corresponds to a measured transmittance of 0.65, compared to a usual transmittance of 0.92 under clean conditions. This was the maximum transmittance loss for the exposure period of the samples, corresponding to a relative decay of about 29%. As shown in Fig. 6 left, the transmittance of the glass decreased linearly with increasing surface dust density. If a linear fit is used to describe the progressive loss of transmittance, the minimum transmittance of the glass at the end of the experiment would be 0.57, corresponding to a relative transmittance loss of 38%. However, in the case of deposited dirt without the disturbances from earthworks, maximum surface dust density reached 0.038 mg cm⁻², which lead to a transmittance decay of 3%.

The effects of soiling can be quantified in terms of photovoltaic power using an electrical spectral model (Ferrada et al., 2017). The model computed the photogenerated current density (J_{ph}) as a function of the solar spectral irradiance (F), the external quantum efficiency of a specific photovoltaic technology (EQE) and the experimental optical transmittance of the glass cover (τ).

The global solar spectral irradiance in the air mass was considered to be 1.5 and is obtained from ASTM G173 -. For the quantum efficiency, a standard monocrystalline silicon solar cell was used as a reference (see Ferrada et al., 2017 for details). The decrease of photo-generated current with surface dust density is shown in Fig. 6 right. Since the transmittance of glass is determined experimentally in the field using silicon photocells, its value is representative of the spectral range and spectral response of each PV technology considered (300 -1200 nm). Thus, the transmittance (τ) is obtained over the entire wavelength range as a broadband value. It is found that the current density drops at a rate of 21 mA cm⁻², thus showing a behavior similar to that of the transmittance, this value corresponds to the point of maximum soiling caused by the work. For a normal month of exposure, the current density is 32 mA cm⁻², which corresponds to losses of 4%.



Fig. 6 Left: Measured transmittance of outdoor exposed PV glass versus surface dust density (Olivares et al., 2019). Right: Estimated photo-generated current density of outdoor exposed glass covers versus surface dust density of samples. Olivares et al., 2019)

4. Conclusions

The impact of earth movements on the soiling properties for photovoltaic modules in the Atacama Desert has been analyzed. The results show that earth movements cause significant changes affecting the geology of the site. These changes are observed in the morphology, granulometry and density of the deposited material. The most significant change is related to the increase of gypsum deposited on the surface of the photovoltaic modules. This implies that processes such as cementation are favored in this period, possibly generating an impact on the way the affected modules must be cleaned. Due to the cementation process, the sand grains are trapped in this process, which implies that cleaning methods must be sought where this glue does not generate abrasion at the time of cleaning.

Another important aspect to consider is that earth movements also generate an increase in material deposition. This increment has a detrimental effect on the proper performance of the PV module. For one month of earthworks, optical losses of 40% were achieved, directly affecting the profitability and projection of a photovoltaic park.

Nevertheless, these disturbances caused by the earth movements were temporary and four months after the work, the original levels of soiling, chemical and morphological composition were found as before the disturbance. To address the negative effects of the construction, it is proposed to use the chemical properties of gypsum (abundant material during the earthworks) and to wet the rubble and the construction site to reduce the impact of dust. This would generate salt crusts that would prevent the increment of suspended material resulting from the earthworks.

This work provides information that allows operators of photovoltaic plants to take the necessary precautions to reduce the effect of soiling caused by artificially created soil movement. In addition, information is provided on how to mitigate the effect of earthworks. In this case, it is recommended to water the soil removed from the working area to achieve a cementation of the soil and not affect the performance of the surrounding PV modules.

5. Acknowledgments

The authors would like to thank projects CONICYT/FONDAP 15110019 Solar Energy Research Center SERC-Chile, ING2030 CORFO 16ENI2-71940 and the PVCastSOIL Project (ENE2017-83790-C3-1, 2 the Chilean Economic Development Agency (CORFO) with contract No 17PTECES-75830 under the framework of the project "AtaMoS TeC" and the generous financial support provided by the GORE-Antofagasta, Chile, Project FICR Antofagasta 2017 BIP code 30488824-0 and the Unidad de Equipamiento Científico "MAINI" of the Universidad Católica del Norte for the support in the preparation of samples, analysis and generation of data through the XRD and SEM team.

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G-05. Power Systems

Transient Simulation and Control strategy of Supercritical CO₂ Solar Thermal Power Generation System

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Abstract

In order to mitigate climate change and promote energy revolution, it is imperative to develop new energy technology of supercritical carbon dioxide (sCO_2) solar thermal power generation. By studying the basic scientific problems of the integration of the sCO_2 Breton cycle with the solar tower (SPT) station, it will contribute to the realization of the zero-carbon scenario. By establishing the dynamic simulation model of the integrated system, the key parameters of the system are determined, and the transient simulation and control strategy are studied. The results show that the efficiency of the system decreases by 3.1% at 75% load operation and 9.5% at 50% load operation compared with 100% load operation. Compared with conventional inventory control, the power generation of the system on the summer solstice and winter solstice after adopting extremum-seeking control increased by 2.06% and 1.61%, after adopting differential evolution control increased by 2.13% and 1.69%. While, when the DNI exceeds 600W/m², extremum-seeking control shows greater advantage compared with differential evolution control. At last, some suggestions on promoting clean energy technology innovation are put forward.

Keywords: Climate change; Supercritical carbon dioxide; Concentrated solar power; Simulation; Control

1. Introduction

Since the nineties of the 20th century, the change of global climate system, which is mainly characterized by climate warming, has become the most severe environmental challenge faced by mankind. A warming climate will threaten food, water, ecosystems, extrmme weather events, risk of abrupt and major irreversible changes and more. As shown in Fig. 1, in order to cope with climate change, from the first World Climate Conference held in Geneva in 1979 to the upcoming COP26 in 2021, countries around the world have formulated relevant policies and taken effective measures. On the occasion of the fifth anniversary of the Signing of the Paris Agreement, China has announced to the world its national goal of achieving carbon peak by 2030 and carbon neutral by 2060. At that time, renewable energy will play a major role and become the main body of energy increment (Chen Y, 2021). Energy technological innovation is a key direction for carbon neutrality in the future. Promoting global technological change through innovation is likely to be a game changer for international climate change action and can reduce the cost of climate change mitigation and adaptation. Concentrated Solar Power (CSP) is considered as one of the most promising renewable energy generation methods due to its relatively mature technology and low impact on the Power grid, which can generate electricity continuously for 24 hours (Wang Z, 2019). As a new energy technology, sCO₂ solar thermal generation technology can not only rationally utilize the greenhouse gas carbon dioxide in the air, but also improve the efficiency of clean energy generation (He Y et al, 2020), its optimized design and dynamic simulation will make corresponding contributions to promoting the energy revolution and mitigating climate change.



Fig. 1: Major international climate governance events

In order to solve the basic problem of the sCO₂ Brayton cycle integrated with SPT station which used solid particle solar receiver (SPSR), it is necessary to carry out optimization design and dynamic simulation analysis of the integrated system. However, most studies have been focusing on the analysis of steady state operations in the integration between the solar heating block and the sCO₂ cycle, respectively (Al-Sulaiman et al, 2015; Cheang, 2015; Daabo, 2017). There is relatively rare literature works have addressed the controllability problems of it. Singh et al. (2013) conducted dynamic and process control analyses for a solar-assisted Brayton cycle utilizing a simple layout. Minh et al. (2018) investigate the dynamic behavior and control for a directheating solar-assisted recompression cycle. Control strategies are developed for the Brayton cycle to reduce the effect of perturbations in the net solar power and sustain stable operation. However, their studies were all based on the control of sCO_2 inventory in the sCO_2 cycle block, without controlling the inventory of working medium in the solar heating block at the same time. Based on the previous work, the dynamic simulation model of the integrated system is established, and the performance of the system is compared and analyzed by using different control strategies. Aiming at the first solar thermal power generation system pre-built in China, which integrates SPSR and sCO₂ Brayton cycle, corresponding control logic of two typical sunsets in summer solstice and winter solstice were preliminarily analyzed, aiming at laying a foundation for the research of predictive control. By establishing models to calculate the effects of particle size, circulating pressure ratio, turbine and compressor inlet temperature, and regenerator end error on the system performance, the parameters of the integrated system were optimized. By combining the non-dominant sorting genetic algorithm with the printed circuit heat exchanger (PCHE) substitute model calculated by the quasi-two-dimensional heat transfer model, the multiobjective optimization of the PCHE thermo-hydraulic performance was realized, and the Pareto optimal solution set of the temperature rise and pressure drop of the target variables and the corresponding dimensional variable variation characteristics were obtained. By using the extremum-seeking control and differential evolution control strategy, the dynamic characteristics of the system are simulated.

2. Optimization Design

As shown in Fig. 2, aiming at the first sCO₂ solar thermal power plant pre-built in China, which integrates quartz tube bundle SPSR, fluidized bed particle/ sCO₂ heat exchanger, PCHE and turbine/ compressor.

During the time with sunlight, the heliostat field reflects and concentrates the sunlight to the SPSR on the top of the tower. The particles, which flow from the cold tank, is heated to a high temperature in the SPSR, and then flow into the hot tank. The mass flow rate of particles in the SPSR is adjusted in accordance with the varying solar irradiation to maintain a constant temperature of particles at the outlet of the SPSR. Part of the particles in the hot tank pass through the heat exchanger to transfer heat to the sCO₂ Brayton cycle, and then return to the cold tank. During the time lacking sunlight, the particles in the hot tank discharge and heat CO₂ in the heat exchanger, and finally is stored in the cold tank. In the sCO₂ Brayton cycle, the low- pressure CO₂ at state 1 is compressed to the high-pressure state 2. Then the high-pressure CO₂ is heated to state 3 in the recuperator by the low-pressure CO₂ which undergoes the process from state 5 to state 6, and subsequently heated to state 4 in the

heater by the particles from the hot tank. The high-temperature and high-pressure CO_2 at state 4 expands in the turbine to state 5, then the exhausted CO_2 undergoes the process from state 5 to state 6 in the recuperator, releasing heat to heat the high-pressure CO_2 at state 2 up to state 3. Finally, the CO_2 at state 6 exits from the recuperator and is cooled down to state 1 in the cooler.



Tab. 1: Design parameters of Badaling sCO₂ Concentrated Solar Power Plant (Wang Z, 2019; Nie F, 2020).

Symbol	Quantity	Value		
Φ	Location	40.4°N 115.9°E		
N _{hel}	Heliostat Number	100		
A _{hel}	Each heliostat size	100 m ²		
$ ho_{hel}$	Mirror reflectance	0.9		
η_{hel}	Optical Efficiency of Field	66.6%		
H_t	Tower height	92 m		
$N_{R,t}$	Quartz tube number of SPSR	20		
$L_{R,t}$	Length of each tube	2.5 m		
D _{R,out}	Outer diameter of quartz tube	110 mm		
$D_{R,in}$	Inner diameter of quartz tube	100 mm		
$ ho_p$	Density of particle	1750 kg·m ⁻³		
D_p	Mean particle diameter	718 μm		
<i>C</i> _{<i>p</i>,<i>p</i>}	Specific heat of particle	(1.76×10 ⁻⁶ T ³ -3.54×10 ⁻ ³ T ² +2.7T+12.7) J/(kg·K)		
k_p	Thermal conductivity of particle	(6.18×10-4T+0.0222) W/(m·K)		
$lpha_p$	Solar weighted absorptance	0.94		
ε_p	Total, normal emittance	0.85		
M _T	Mass of hot/cold tank	25 t		
M _p	Mass of particles stored in the tank	10 t		
q_L	Heat loss power of hot/cold tank	600 W/ m ²		
T_h	Temperature of hot tank	1073 K		
T _c	Temperature of cold tank	823 K		

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S _{HX}	Shell size of HX	4.5m×2m×4.5m		
$N_{HX,t}$	Tube number of HX	28		
$L_{HX,t}$	Total length of a single tube	28.8 m		
$ ho_{HX,t}$	Density of HX tube	9000 kg·m ⁻³		
D _{HX,in}	Inner diameter of HX tube	36 mm		
D _{HX,ex}	External diameter of HX tube	45 mm		
V _{air}	Air volume in the fluidized bed	3820 N·m³/h		
$m_{HX,p}$	Mass flow rate of particle in the HX	30 t/h		
$m_{HX,CO2}$	Mass flow rate of sCO ₂ in the HX	16.6 t/h		
P _{HX,w}	Pressure of fluidized wind	54.5 kPa		
$P_{HX,p}$	Pressure of particle side	0.101 MPa		
P _{HX,CO2}	Pressure of sCO ₂ side	15.7 MPa		
T _{t,in}	Turbine inlet temperature	823 K		
P _{t,in}	Turbine inlet pressure	14.1 MPa		
$\eta_{k,t}$	Pressure ratio of turbine	1.602		
$\eta_{t,is}$	Turbine isentropic efficiency	74%		
s _t	Speed of turbine	20000 rpm		
W _t	Shaft power of turbine	528 kW		
T _{c,in}	Compressor inlet temperature	308 K		
P _{c,in}	Compressor inlet pressure	8.2 MPa		
$\eta_{k,c}$	Pressure ratio of compressor	1.829		
$\eta_{c,is}$	Compressor isentropic efficiency	73.5%		
S _c	Speed of compressor	28000 rpm		
W _c	Shaft power of compressor	170 kW		
η_g	Generator efficiency	97%		
η_m	Motor efficiency	90%		
S _{re}	Size of recuperator	903mm×314mm×450mm		
T _{r,in,h}	Inlet temperature of hot side	789.6 K		
T _{r,out,h}	Outlet temperature of hot side	342.8 K		
T _{r,in,c}	Inlet temperature of cold side	332.8 K		
T _{r,out,c}	Outlet temperature of cold side	691.74 K		
S _c	Size of cooler	900mm×290mm×450mm		
T _{c,in,h}	Inlet temperature of hot side	362.8 K		
T _{c,out,h}	Outlet temperature of hot side	308 K		
T _{c,in,c}	Inlet temperature of cold side	298 K		
T _{c,out,c}	Outlet temperature of cold side	311 K		
ΔP_{PCHE}	Pressure drop of PCHE	0.3 MPa		
m _{cyc,CO2}	Mass flow rate of sCO ₂ in the turbine /compressor/PCHE	36 t/h		

To analyze the system, the mathematical model of relevant components is established based on the law of conservation of energy, using the mult-section lumped parameter method. And each sub-model is verified. For Heliostat field, the energy delivered from it can be calculated as:

$$Q_{rec} = Q_{solar} \cdot \eta_{hel} = DNI \cdot A_{hel} \cdot \eta_{hel}$$
(eq.1)
Where Q_{rec} is the effective heat gain of the receiver, W; Q_{solar} is the incident solar energy, W.

For solid particles in the SPSR, the microelement segment ΔL is taken as the modeling object, the energy conservation can be calculated as:

$$c_{p}\rho_{p}V_{p}\frac{dT_{p}}{dt} = (c_{p,\text{in}}m_{p,\text{in}}T_{p,\text{in}} - c_{f,\text{out}}m_{p,\text{out}}T_{out}) + (q_{rec,p} - q_{rad,p-qt} - q_{conv,p-qt}) \cdot \Delta L$$
(eq.2)

Where c_p is the specific heat capacity of particles, J/(kg·K); ρ_p is the density of particles, kg·m⁻³; V_p is the volume of particles, m³·kg⁻¹; m_p is the mass flow rate of particles, kg·s⁻¹.

The heat flux absorbed by solid particles is:

$$q_{rec,p} = \tau_{qt} \alpha_p q_{rec} \tag{eq.3}$$

Where c_p is the specific heat capacity of particles, J/(kg·K); τ_{qt} is the transmittance of quartz glass tube.

The radiant heat flow between the solid particles and the inner wall of the quartz tube is:

$$q_{rad,p-qt} = \frac{\sigma \pi D_{in} \left(T_p^4 - T_{qt}^4\right)}{1/\varepsilon_p + 1/\varepsilon_{qt} - 1}$$
(eq.4)

Where σ is the Stefan Boltzmann constant; T_p and T_{qt} are average temperature of particles and quartz glass tube, K; ε_p and ε_{qt} are the emittance of particles and quartz glass tube.

The convective heat flow between the solid particles and the inner wall of the quartz tube is:

$$q_{conv,p-qt} = h_{p,qt} \pi D_{in} \left(T_p - T_{qt} \right)$$
(eq.5)

Where $h_{p,qt}$ is the heat transfer coefficient between particles and quartz tube, W m⁻² K⁻¹.

The convective heat transfer correlation formula is calculated using the research method of Albrecht and Ho (2018) for the convective heat transfer between solid particles and the wall surface in the horizontal push flow in the rectangular flow passage. The solid particles in the flow passage are regarded as the continuous medium with constant flow distribution:

$$h_{p,qt} = \frac{\lambda_{eff}}{D} \overline{Nu_q} = \frac{\lambda_{eff}}{D} \left[\left(2 \times \frac{0.886}{\sqrt{Gz^{-1}}} \right)^{12/5} + 12^{12/5} \right]^{5/12}$$
(eq.6)

Where λ_{eff} is the Thermal conductivity of particles, W m⁻¹ K⁻¹; Nu_q and Gz^{-1} are dimensionless number.

For TES, the energy conservation can be calculated as:

$$\frac{d\left(M_{hot,\tan k}\cdot c_{p}\cdot T_{p,hot,\tan k}\right)}{dt} = m_{rec}\cdot c_{p}\cdot T_{p,hot,\tan k} - m_{HX}\cdot c_{p}\cdot T_{p,HX,out} - Q_{loss,hot,\tan k}$$
(eq.7)

$$\frac{d\left(M_{cold,\tan k} \cdot c_{p} \cdot T_{p,cold,\tan k}\right)}{dt} = m_{HX} \cdot c_{p} \cdot T_{p,HX,out} - m_{rec} \cdot c_{p} \cdot T_{p,cold,\tan k} - Q_{loss,cold,\tan k}$$
(eq.8)

Where $M_{hot,tank}$ and $M_{cold,tank}$ are quality of high temperature tank and low temperature tank, kg; m_{HX} and m_{rec} are mass flow rate of heat exchanger and receiver, kg s⁻¹.

For the gas-solid mixing side, the tube and sCO₂ side of the HX, the energy conservation can be calculated as:

$$\left(c_{p,p}\rho_{p}V_{p}+c_{p,g}\rho_{g}V_{g}\right)\frac{dT_{m}}{dt}=\left(-q_{rand,m-t}-q_{conv,m-t}\right)\cdot\Delta L+\left(c_{p,p}m_{p}+c_{p,g}m_{g}\right)\left(T_{m,in}-T_{m,out}\right)$$
(eq.9)

$$c_{p,t}\rho_t V_t \frac{dT_t}{dt} = \left(q_{rand,m-t} + q_{conv,m-t} - q_{conv,t-CO_2}\right) \cdot \Delta L$$
 (eq.10)

$$c_{p,CO_2}\rho_{CO_2}V_{CO_2}\frac{dT_{CO_2}}{dt} = q_{conv,t-co2} \cdot \Delta L + c_{p,CO_2,in}m_{CO_2,in}T_{CO_2,in} - c_{p,CO_2,out}m_{CO_2,out}T_{CO_2,out}$$
(eq.11)

Where $c_{p,p}$, $c_{p,t}$ and c_{p,co_2} are specific heat capacity of particles, tube and carbon dioxide, J/(kg·K); ρ_p , ρ_t and ρ_{co_2} are density of particles, tube and CO₂, kg·m⁻³; V_p , V_t and V_{co_2} are volume of particles tube and CO₂, m³·kg⁻¹; m_p , m_g and m_{co_2} are the mass flow rate of particles, gas and CO₂, kg·s⁻¹.

Radiant heat flux is:

$$q_{rand,m-t} = \frac{\sigma \pi D_{out} \left(T_m^4 - T_t^4 \right)}{1/\varepsilon_p + 1/\varepsilon_t - 1} \tag{eq.12}$$

Where T_m and T_t are average temperature of fluidized particles and heat exchanger tube, K. Convective heat flux is:

$$q_{conv,m-t} = h_{conv,m-t} \pi D_{out} \left(T_m - T_t \right)$$
(eq.13)

Where $h_{conv,m-t}$ is the heat transfer coefficient between fluidized particles and heat exchanger tube, W m⁻² K⁻¹. The convective heat flux between the heat exchange tube and the CO₂ in the tube is:

$$q_{conv,t-CO_2} = h_{conv,t-CO_2} \pi D_{in} \left(T_t - T_{CO_2} \right)$$
(eq.14)

Where $h_{conv,t-co_2}$ is the heat transfer coefficient between heat exchanger tube and CO₂, W m⁻² K⁻¹.

The heat-transfer coefficient from the correlations of Borodulya (1991) and Gnielinski (1976):

$$h_{conv,m-t} = Nu_p \frac{\lambda_g}{d_p} = \left(0.74 A r^{0.1} \left(\frac{\rho_p}{\rho_g}\right)^{0.14} \left(\frac{Cp_p}{Cp_g}\right)^{0.14} \left(1-\varepsilon\right)^{2/3} + 0.46 \operatorname{Re} \operatorname{Pr} \frac{\left(1-\varepsilon\right)^{2/3}}{\varepsilon}\right) \frac{\lambda_g}{d_p}$$
(eq.15)

$$h_{conv,t-CO_2} = Nu_{CO_2} \frac{\lambda_{CO_2}}{d_{hd}} = 0.0214 \left(\operatorname{Re}_{CO_2}^{0.8} - 100 \right) \operatorname{Pr}_{CO_2}^{0.4} \left[1 + \left(\frac{D_{in}}{L} \right)^{2/3} \right] \left(\frac{T_{CO_2}}{T_i} \right)^{0.45} \frac{\lambda_{CO_2}}{D_{in}}$$
(eq.16)

For PCHE, equal heat flow method was used in the model. When the total heat transfer is fixed, the total heat transfer is divided into N parts.

$$c_{Ph,j}m_h(T_{hj,i} - T_{hj,o}) = c_{Pc,j}m_c(T_{cj,o} - T_{cj,i}) = \frac{Q_{lot}}{N} = U_jA_j\Delta T_j$$
(eq.17)

In the sinusoidal flow channel of the recuperator, the correlation equation between heat transfer and resistance of sCO_2 are:

$$Nu = 0.246Re^{0.6513}Pr^{1.5647}$$
 (eq.18)

$$f = 5.5119 Re^{-0.35}$$
 (eq.19)

On the water side of the precooler, the correlation equation of heat transfer and resistance are:

$$Nu = 0.062063Re^{0.765}$$
 (eq.20)

$$f = 16.79364Re^{-0.368}$$
 (eq.21)

On the sCO₂ side of the precooler, the correlation equation of heat transfer and resistance are:

$$Nu = 0.0506Re^{0.8356}$$
 (eq.22)

$$f = 524.0253Re^{-0.6743}$$
 (eq.23)

For the turbine and compressor, the model is referenced from SNL (Conboy, 2012; Wright, 2011):

$$m_{co_2} = C_T A_{eff} \rho_{T,out}$$
, $C_T = \sqrt{2\Delta h_{T,is}}$ (eq.24)

$$\phi^{*} = \frac{m_{co_{2}}}{\rho U_{c} D_{c}^{2}} \left(\frac{N}{N_{design}}\right)^{1/5}, \quad \psi^{*}_{i} = \frac{\Delta h_{i}}{U_{c}^{2}} \left(\frac{N_{design}}{N}\right)^{(20\phi^{*})^{3}}, \quad \eta^{*} = \eta \left(\frac{N_{design}}{N}\right)^{(20\phi^{*})^{3}}$$
(eq.25)

For the integrated system, the sCO₂ cycle efficiency and net power generation efficiency are respectively:

$$\eta_{sCO_2} = \frac{(h_{T_{in}} - h_{T_{out}}) \cdot \eta_G - (h_{C_{out}} - h_{C_{in}}) / \eta_{motor}}{h_{T_{in}} - h_{HX_{in}}}$$
(eq.26)

$$\eta_{solar-el} = \frac{\sum_{t} P_{el,solar} \cdot \Delta t}{\left(\sum_{t} DNI \cdot A_{hel} \cdot \Delta t\right) \cdot \left(\frac{\sum_{t} Q_{solar-cycle} \cdot \Delta t}{\sum_{t} Q_{solar-TFS} \cdot \Delta t}\right)}$$
(eq.27)

Where $h_{T_{in}}$ and $h_{T_{out}}$ are enthalpy of turbine inlet and outlet, $J \cdot kg^{-1}$; $h_{C_{in}}$ and $h_{C_{out}}$ are enthalpy of compressor inlet and outlet, $J \cdot kg^{-1}$; $h_{HX_{in}}$ is enthalpy of heat exchanger inlet, $J \cdot kg^{-1}$; η_G and η_{motor} are efficiency of generator and motor; $P_{el,solar}$ the net solar power generation, W; $Q_{solar-cycle}$ and $Q_{solar-TES}$ are solar energy input into the power cycle and transferred to the heat storage tank, W.

After clarifying the operating mechanism of the system, the key parameters in the system, such as particle size, circulating pressure ratio, turbine and compressor inlet temperature, and regenerator end error, are optimized and designed.



Fig. 3: Particle size selection

Fig. 4: Pressure ratio selection

As the heat medium, particles directly affect the efficiency of solar receiver and the performance of heat exchanger. As shown in Fig. 3, when the particle size is 0.5mm, simultaneously guarantee efficiency of receiver and coefficient of heat transfer of heat exchanger.

Cycle pressure ratio directly affects turbine power output and compression power consumption. As shown in Fig. 4, when the cycle pressure ratio greater than 2.6, with the increase of it, compression power consumption rises above the turbine output power increase amplitude. The main reason is: at this time the compressor inlet parameters near the CO_2 critical point, the CO_2 density are greatly influenced by pressure and temperature, the small changes of the pressure can lead to large fluctuations in the density, thus bring larger compression power consumption change. When the pressure ratio is 2.6, simultaneously guarantee specific work and cycle efficiency.



Fig. 5: Compressor inlet temperature selection

Fig. 6: Turbine inlet temperature selection

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Compressor inlet temperature will directly affect the compression and cooling process, so it is an important parameter in the sCO₂-CSP system. As shown in Fig. 5, In the simple regenerative cycle, with the increase of the compressor inlet temperature, compression work consumption rise cycle specific work is reduced, which cause a decline in cycle efficiency. However, compressor inlet temperature increases, the heat release of sCO₂ in cooler decreases, loop heat loss is reduced, the cycle heat loss reduction is beneficial to promote the efficiency of circulation. Therefore, the cycle efficiency of simple heat recovery cycle increases first and then decreases under the dual influence of cycle specific work and cycle heat loss. When the compressor inlet temperature is 33 °C, cycle thermal efficiency is the highest.

Turbine inlet temperature is also one of the important parameters affecting system performance. As shown in Fig. 6, with the increase of turbine inlet temperature, the solar heat collection temperature increases, and the heat loss of the solar receiver also increases, resulting in the decrease of receiver efficiency, and then the decrease of solar heat collection efficiency. Due to the dual influence of cycle thermal efficiency and solar heat collection efficiency, there exists an optimal turbine inlet temperature to make solar power generation efficiency reach the maximum value. When the turbine inlet temperature is 650-700 $^{\circ}$ C, simultaneously guarantee cycle efficiency and power generation efficiency.



(a) Pareto optimal solution obtained by optimization

(b) Size corresponding to the Pareto optimal solution



Besides, in order to establish the relationship between the design variables and the target variables, the multiobjective optimization method adopts NSGA-II. Firstly, a group of random groups is generated in the design variable space. Then, each individual in the group was evaluated with the adaptive equation, that is, the established substitute equation; Then, the individuals in the group were ranked based on the non-dominant ranking method, and the sub-groups were generated by binary league selection, crossover and mutation operations, with the probability of crossover and mutation being 0.9 and 0.1, respectively. The original group and subgroups were combined into a new group, the new group was sorted by non-dominant order, and each individual was given a crowding factor parameter. The next generation's group will consist of well-adjusted individuals from the previous generation's group. Such iterative calculation, until the maximum number of iterations, the final result will be Pareto optimal solution, as shown in Fig. 7. To obtain the optimal Pareto solution and its corresponding size distribution, the pressure drop of PCHE after optimization can be reduced compared with the reference heat exchanger26%, or a 0.4% increase in the temperature of the cold side fluid.

3. Dynamic Simulation

The transient simulation was done on TRNSYS. While the thermodynamic and transport properties of sCO_2 are determined with the assistance of NIST database embedded in TRNSYS.

Due to the intermittent nature of solar irradiation, it is necessary to study the variation of the net output power and different efficiency of the system on typical days under different meteorological conditions with time. Based on the study of simulation system, the dynamic variation rule of thermodynamic performance of typical day system on spring equinox and autumn equinox is analyzed. The results show that with the increase of solar radiation intensity, the heat collection efficiency and the total amount of solar heat collection increase, and the system output work, thermal cycle efficiency and solar net power generation efficiency also increase. This is because when the heat collection efficiency and the total amount of solar heat collection increase, in order to ensure that the parameters of

each node of the system are stable around the design parameters, the flow of the working medium of the thermal circulation increases, and the efficiency of the compressor and turbine is also raised to near its rated efficiency, so that more net output work can be obtained. As shown in Fig. 8, the net output power of the system in a typical day can reach 200kW, and then the thermodynamic cycle efficiency and solar net power generation efficiency of the system reach their maximum 41.35% and 23.02%, respectively.



Fig. 8: Variation law of thermal performance of the system on typical day

Tab. 2: Cycle operation parameters under different loads									
	100% load			75% load			50% load		
	T P m		m	T P m			Т	Р	m
	/°C	/MPa	/kg·s-1	/°C	/MPa	/kg·s-1	/°C	/MPa	/kg·s-1
Inlet of	32	7.6	1.732	32	7.6	1.475	32	7.6	1.183
compressor									
Outlet of	74	20	1.732	68	17.6	1.475	61	15.1	1.183
compressor									
Inlet of HX	385	20	1.732	402	17.6	1.475	423	15.1	1.183
Inlet of turbine	600	20	1.732	600	17.6	1.475	600	15.1	1.183
Outlet of turbine	479	7.6	1.732	495	7.6	1.475	514	7.6	1.183
Inlet of cooler	79	7.6	1.732	73	7.6	1.475	66	7.6	1.183
Cycle efficiency	42.83%			41.52%			38.75%		

4. Control Research

The running state of the whole system is initially designed as nine modes as shown in Fig. 9, and the program is carried out on TRNSYS simulation platform for each kind of running mode, which lays the foundation for the realization of control logic.



Fig. 9: sCO₂-CSP system operation mode

Different control strategies were to be used to study the operation of the system.

As shown in Fig. 10 (a), the conventional control strategy is fixed inventory control. Fixed carbon dioxide specific charge in the cycle provided sufficient performance on the design conditions. The "master" controller (PI1) decides the set-point for loop inventory to achieve the Turbine inlet temperature set-point. The "slave" controller (PI2) manipulates the carbon dioxide withdrawal /addition flowrate to track the loop inventory set-point proposed by the PI1.

As shown in Fig. 10 (b), one advanced control strategy is extremum-seeking control. Unlike the fixed inventory controller, in the extremum-seeking control approach, the particle/CO2 inventory can vary with time and the plant input is the inventory rate of change (θ). A sinusoidal dither is applied to the plant input to provide persistency of excitation in the gradient estimates at the output of the high pass filter. Inventory addition and removal is conducted at the compressor inlet to minimize any involved parasitic power losses. The proposed cost function (J) needs to incorporate the net power as well as the operating constraints on turbine inlet temperature and pressure. These operating constraints are considered through the introduction of slack variables. By changing the sign of the cost function and the high-pass filter, the extremum-seeker may be equally posed as a maximum or minimum seeking scheme.

The nonlinear slack variable operator is defined as:

$$\Gamma(x,y) = \begin{cases} 0 & \text{if } a < b \\ a-b & \text{if } a < b \end{cases}$$
(eq.28)

The cost function being proposed as:

$$J = P_{net} - \alpha \Gamma \left(T_{t,in}, T_{maximum} \right) - \beta \Gamma \left(p_{t,in}, p_{maximum} \right)$$
(eq.29)

Where α and β represent Slack variable weights, $T_{t,in}$ and $p_{t,in}$ represent inlet temperature and pressure of turbine.

As shown in Fig. 10 (c), the other advanced control strategy is differential evolution control. The basic idea of the control strategy from the initial turbine inlet temperature set point, use the net output power populations from different system randomly selected from the difference between the two individuals and vector as the third source of random variation, the individual will be poor after vector weighted sum according to certain rules and the third individual variation individuals, this operation is called mutation. Then, the variation individuals are mixed with the pre-determined system net output power target individuals to generate test individuals, a process called crossover. If the fitness value of the test individual is better than that of the target individual, the test individual will replace the target individual in the next generation; otherwise, the target individual will still be preserved. This operation is called selection. In the evolution process of each generation, each individual through continuous iterative calculation to guide the search process to approach the global optimal solution.



(a) Conventional fixed inventory control



(b) Extremum-seeking control



(c) Differential evolution control

Fig. 10: Different control strategies

Compared with the conventional fixed inventory control mode in the typical day with same number hours' heat storage. As shown in Fig. 11 (a), on the summer solstice, net solar power drops are small and unstable, the electricity production powered by extremum-seeking control is 1649.3kW, improved by 2.06%; the electricity production powered by differential evolution control is 1650.5kW, improved by 2.13%. As shown in Fig. 11 (b), on the winter solstice, net solar power drops significantly and permanently, the electricity production powered by differential evolution control is 1.61%; the electricity production powered by differential evolution control is 1.61%; the electricity production powered by differential evolution control is 1.210.4kW, improved by 1.61%; the electricity production powered by differential evolution control is 1.211.3kW, improved by 1.69%. However, when the DNI exceeds 600W/m², extremum-seeking control shows greater advantage compared with differential evolution control.



5. Conclusion

In this study, the basic thermodynamic properties of the supercritical carbon dioxide solar thermal power system were analyzed, the key parameters of the system were optimized and the dynamic simulation was carried out. Particle size is 0.5mm, simultaneously guarantee efficiency of receiver and coefficient of heat transfer of heat exchanger; Pressure ratio is 2.6, simultaneously guarantee specific work and cycle efficiency; Turbine inlet temperature is 650-700 °C, simultaneously guarantee cycle efficiency and power generation efficiency; Compressor inlet temperature is 33 °C, cycle thermal efficiency is the highest.

Based on dynamic simulation, different control strategies are studied, which has certain guiding significance for the efficient operation of the experiment. By comparing simulation results of different control strategies, extremum-seeking control of the system can be increased by 2.06%, differential evolution control of the system can be increased by 2.13%. However, when the DNI exceeds 600W/m², extremum-seeking control shows greater advantage compared with differential evolution control.

Work in progress also includes multi-condition experiment, multi-mode Control and multi-angle analysis. Related study aims to provide specific basic scientific research and route guidance for clean energy.

Clean energy innovation is critical to achieving net zero emissions and mitigating climate change. The energy sector can only achieve net zero emissions if there is a strong global push for clean energy innovation. There is a disconnect between climate targets set by governments and companies and efforts to develop better, lower-cost technologies. While tremendous advances in technologies such as solar have been witnessed, further changes are

needed in the pace of innovation and the scale of deployment of new technologies. Policy suggestions for promoting clean energy technology innovation are as follows:

• Determine innovation priority, track and adjust innovation progress. Review selected projects that require a mix of technologies that require public support to ensure that technological innovations are rigorous, collective, flexible, and consistent with local strengths.

• Promoting public research and development and market-led indigenous innovation. Scale up funding for different technologies using a range of tools, from public research and development to market incentives.

• Solve the problems in the clean energy innovation value chain. Look at the big picture and ensure that all components of the key value chain are advancing evenly towards the next market application and one exit effect.

• Build and enable infrastructure. Mobilize private financing to help companies cross the "valley of death" by co-sharing networks to enhance the investment risk of commercial scale demonstrations.

• Strive for regional innovation success on a global scale. Collaborate and share best practices, experiences and resources through existing multilateral platforms to address pressing global technological challenges.

Further in-depth research will be conducted on this new energy technology to promote the energy revolution, mitigate climate change, and make contributions to international climate governance and zero-carbon development.

6. Acknowledgments

The authors would like to thank the research grant support from the National Key Research and Development Project of China (No.2018YFB1501005).

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Novel Hybrid GWO–IC based MPPT Technique for PV System under Partial Shading Conditions

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Abstract

This study presents the possible solution to the problem of extraction of maximum power from PV systems under non-uniform irradiance such as partial shading condition (PSC). The grey wolf optimization (GWO) and Incremental Conductance (IC) MPPT methods are integrated to design a hybrid MPPT approach so as to extract maximum possible power from PV modules under partial shading conditions. In this technique, GWO operates in the early stages to track the MPP, while IC operates in the latter stages for higher tracking efficiency and faster convergence to the global peak. The proposed hybrid-MPPT technique is simulated for a 1 kWp PV system using MATLAB/SIMULINK tool. The designed model is studied for two different configurations i.e. 4S and 2S2P topologies under different shading patterns to verify its effectiveness under rapidly varying irradiance. The simulated results clearly indicate that the proposed hybrid MPPT exhibits higher tracking efficiency (>99%), faster convergence to the global peak with minimal time (<0.1s), negligible oscillations around MPP and thereby enables it to extract the maximum possible power from the PV system as compared to P&O, IC, and GWO based MPPT methods.

Keywords: Hybrid MPPT, Grey Wolf Optimization (GWO), Incremental Conductance, Partial Shading Conditions.

1. Introduction

Solar photovoltaic (PV) systems have drawn great attention and become a significant energy source in various applications because of its impressive advantages such as environmental friendliness, inexhaustible resources, free to harvest, cost competitiveness, and minimal maintenance. The photovoltaic systems are considered clean and sustainable energy sources. The PV system performance depends on solar radiation, ambient temperature, soiling, and shading, etc. Some other factors like the design and installation of the systems i.e. tilt, orientation, and string configurations also affect the energy production of the photovoltaic system. Therefore, to extract maximum power from a PV module or array, various maximum power tracking (MPPT) systems have been developed to optimize its operating voltage by switching the dc-dc boost converter. These MPPT approaches enable the PV system in transferring the maximum possible power generated to the load or grid by regulating the converter's duty ratio according to the changes in weather conditions. Under uniform solar irradiance, the MPP can easily be tracked by using the conventional MPPT algorithms as these methods are based on a simple peak detection of the P-V characteristic curve. However, these conventional techniques fail to detect MPP under partial shading conditions (PSCs) with rapid changes in solar insolation. In the event of non-uniform solar insolation or during PSCs, triggering of the bypass diodes to disintegrate the shaded modules from the array, generates numerous peaks i.e., various local peaks (LP) and one global peak (GP). These create a serious challenge to the conventional MPPTs in order to differentiate between these local and global maxima.

Saravanan and Babu, (2016) presented a detailed review on various real-time MPPTs based on Perturbation and Observation techniques (such as fixed step P&O, variable step size P&O, multivariable P&O, PSO based P&O, hybrid P&O MPPT); Incremental Conductance technique (such as modified IC, variable step IC, improved variable step IC, power increment based IC, modified adaptive IC); Intelligent MPPT techniques (such as FLC, Neural Network, ANFIS, FL-GA); and Partial Shading based MPPT techniques (such as Improved PSO, Deterministic PSO, Dormant PSO). These methods mainly vary in terms of complexity in the algorithm, speed of convergence, oscillations near the MPP, required electronic components for its integration, and cost. In order to overcome these tracking problems being associated with the conventional MPPTs, several advanced computing

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and meta-heuristic techniques have been introduced such as Whale Optimization (WO) (Premkumar and Sowmya, 2019), Grey Wolf Optimization (GWO) (Mirjalili et al., 2014), Flower Pollination (Shang et al., 2018), Cuckoo Search (Peng et al., 2018), Jaya algorithm (Huang et al., 2018), Fireflies (Sundareswaran et al., 2014), Artificial Neural Network (ANN) (Rizzao and Scelba, 2015), Artificial Bee Colony (ABC) (Benyoucefa et al., 2015), Particle Swarm Optimization (PSO) (Liu et al., 2012), and so on. These methods are primarily based on search and optimization approach and can detect the global peak correctly and as a result, the performance of the PV system improves. The major drawbacks associated with these techniques are slow tracking speed and higher complexity than the conventional algorithms. However, these methods are effective in accurately determining the MPP.

Yilmaz et al. (2019) has adopted an improved FLC MPPT based on two blocks (i) calculation block to calculate the operating voltage point of MPP and (ii) FLC block for adjusting the duty ratios of PWM waveform that switches the dc-dc boost converter according to changes in environmental conditions. The study compared the performance with the conventional MPPTs such as FLC, P&O and IC techniques and has claimed that the efficiency of the proposed method is found between 99.5% - 99.9% and the duration in reaching GP is measured to be 0.021 sec. Premkumar et al. (2019) has presented a bio-inspired Whale Optimization (WO) MPPT method that tackles rapid environmental changes specially PSCs. The study concluded that the proposed algorithm, under partial shading conditions resulted in tracking efficiency of more than 95% and the convergence time is less than 0.15 sec. Shang et al. (2018) has proposed a unique MPPT method using Flower Pollination (FP) algorithm, developed by Yang et al. (2013), that reduces the start-up time and steady-state power oscillation by implementing an effective iterative termination strategy once the GP is tracked and exhibits better system response speed and higher tracking efficiency under rapid changes in irradiance and PSCs compared with the traditional P&O and PSO MPPT methods.

Another advanced soft computing technique called Grey Wolf Optimization (GWO), first developed by Mirjalili et al. (2014), was inspired by the hunting techniques of grey wolves for attacking prey. Mohanty et al. (2016) has implemented this approach for designing a robust MPPT technique to deal with the rapid environmental changes in solar irradiance and PSCs. This study has compared the proposed GWO technique with the conventional P&O and an Improved Particle Swarm Optimization (IPSO) technique and has observed that the algorithm performs better in terms of tracking speed, accuracy, convergence rate, and steady-state oscillations. However, this GWO method exhibits computational complexity. Later to overcome this, a new hybrid MPPT algorithm is proposed that uses both GWO and P&O technique where GWO operates during the initial stages for tracking of the MPP and P&O algorithm during the final stages so as to achieve faster convergence towards the GP compared to the former one (Mohanty et al. 2017). Jiang et al. (2015) have proposed a hybrid-ANN method where ANN is merged with P&O to achieve GP at a better convergence rate. The ANN tracks the GP during the initial stage, and finally, P&O locates the MPP under PSC. Several other hybrid MPPTs are also introduced such as hybrid-WO (Premkumar and Sumithira, 2018), hybrid-PSO (Farh et al., 2018), Hybrid-Jaya (Huang et al., 2019), etc. to improve the convergence speed in reaching MPP.

This study proposes a novel hybrid GWO-IC MPPT algorithm that has greater significance than other techniques due to its explorative and exploitative capability, as well as its ability to avoid local peaks. The proposed algorithm's search time is lower without sacrificing its accuracy by lowering the number of search agents. As a result, the convergence time is also getting considerably reduced due to the lower number of search agents. Furthermore, the algorithm quickly tracks and reaches the MPP, with minimal power oscillation in the steady-state. The rest of this paper is structured as follows. Section 2 describes the modeling of the PV module and its characteristics under PSCs. Section 3 presents the overview of the proposed algorithm and its role in designing for the MPPT application. Section 4 presents the simulation results and discussions. Lastly, the paper is concluded in Section 5.

2. PV Characteristics under PSCs

2.1 Mathematical modeling of PV module

Fig. 1 depicts the equivalent circuit of a typical solar cell, which includes a light-driven current source, a shunt resistance, a series resistance, and a diode. Using the equivalent circuit, the characteristic equation that links to

output voltage and current is presented in equation 1 (Ahmed and Salam, 2015).

$$I = I_{PV} - I_o[exp(\frac{V + IR_S}{V_T}) - 1] - (\frac{V + IR_S}{R_P})$$
(eq. 1)

Where, I_{PV} indicates PV current (in A), R_s indicates series resistance (in Ω), I_0 represents reverse saturation current (in A), R_{sh} is shunt resistance (in Ω), V is output voltage (in V) and V_T indicates thermal voltage of the PV module and is given by:

$$V_T = \frac{nkT}{q}$$
(eq. 2)

Where, q indicates electronic charge $(1.6 \times 10^{-19} \text{ C})$, n indicates diode factor, T indicates module temperature (K), and k indicates Boltzmann Constant $(1.38 \times 10^{-23} \text{ J/K})$. The current generated from the PV module can be expressed as:

$$I_{PV} = \frac{G}{G_{STC}} (I_{PV,STC} + K_t.\Delta T)$$
 (eq. 3)

Where $I_{PV, STC}$ indicates the PV module current at Standard Test Condition (STC), G_{STC} indicates solar irradiation under STC, G indicates irradiation falling on surface of PV module, and K_t indicates temperature coefficient of PV current.



Fig. 1: Equivalent circuit of a typical solar cell

The parameters of a PV module or manufacturer ratings are based on STC which include the temperature of 25°C, irradiation of 1000 W/m², and air mass of 1.5. Fig. 2 presents the typical solar cell characteristics profile under STC. For maximum power extraction or optimum production from PV systems, its installation depends on site such as longitude and latitude of the location, orientation factors such as tilt angle and altitude etc. It also depends on various environmental factors such as humidity, ambient temperature, dust, etc. and the module technology such as poly-crystalline, mono-crystalline, amorphous, thin film etc.



Fig. 2: Characteristic curve of a PV cell at STC

2.2 Description of PV system

A PV system consists of a number of PV modules connected in series and parallel combinations. When a PV module subjected to PSCs, the shaded PV cell functions as a resistive load and causes local overheating or hotspots by dissipating a high amount of power from the energy generated by the unshaded cells. This overheating may

lead to permanent damage of the cell, and even cracking of protective glass. In order to protect these modules from shading effects, PV systems are nowadays installed with a power diode, called the bypass diode to bypass the shaded cells or modules. The inclusion of these bypass diodes across a PV module results in numerous local peaks in P-V and multiple steps in its I-V characteristics. Therefore, it is necessary to investigate the characteristics of the systems for both uniform and non-uniform solar insolation levels.



Fig. 4: Shading patterns (a)-(b) 4S configuration (c)-(d) 2S2P configuration

The designed model is studied for two different configurations i.e. 4S and 2S2P topologies under different shading patterns. Fig 3a-b shows the 4S configuration where four modules are connected in series. Fig 3c-d presents the 2S2P configuration where four PV modules are connected separately in two parallel configurations, each consists of two serially connected PV modules. Fig 4a-b presents the P-V curves for 4S configuration with clearly labeled GP and LP locations under two different shading patterns, i.e., Pattern I and Pattern II respectively. Similarly, the P-V curves for 2S2P configuration at two different shading patterns, i.e., Pattern III and Pattern IV are respectively shown in Fig 4c-d.

3. Overview of Proposed MPPT Method

3.1 Grey Wolf Optimization and its role in designing of MPPT

The GWO algorithm adopted by Mirjalili et al. (2014) has received immense acceptance in determining efficient global optimum solutions compared to other meta-heuristic approaches. The GWO approach mimics the natural leadership hierarchy and the hunting strategy of grey wolves while attacking prey. Grey wolves are categorized into four types: alpha (α), beta (β), delta (δ), and omega (ω). They are regarded as the top of the food chain, and like to stay in packs with a strict social dominating hierarchy, as seen in Fig 5. In order to design the GWO technique, the social hierarchy of the wolves is mathematically modelled by assuming alpha (α) to be the fittest candidate. While, beta (β) and delta (δ) is regarded as the second and third best solutions, respectively and omega (ω) are regarded as the remaining candidate solutions. Fig 6 presents the three primary steps of the GWO algorithm for executing the optimization process are: (a) chasing and tracking prey, (b) encircling and harassing the prey unless it stops changes direction, and (c) attacking the targeted prey.



Fig. 5: Hierarchy of grey wolf (dominance decreases from top down)



Fig. 6: Hunting behavior of grey wolves: (A) chasing and tracking prey (B-D) harassing and encircling (E) attacking the prey

During the hunt, these wolves encircles the prey and the following set of equations can be used to model their encircling behavior:

$$\vec{E} = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)| \qquad (eq. 4)$$

$$\vec{X}(t+1) = \vec{X_p}(t) - \vec{A}.\vec{E}$$
 (eq. 5)

Where t is the current value of iteration, \vec{A} , \vec{C} and \vec{E} are coefficient vectors, $\vec{X_p}$ denotes the position vector of prey, and \vec{X} denotes the wolf's position vector. The \vec{A} and \vec{C} vectors are computed in the following manner:

$$\overrightarrow{A} = 2\overrightarrow{a} \cdot \overrightarrow{r_1} \cdot \overrightarrow{a} \qquad (eq. 6)$$

$$\overrightarrow{C} = 2 \cdot \overrightarrow{r_2} \qquad (eq. 7)$$

Where \vec{a} component is linearly declined from 2 to 0 during the iteration process and r_1 , r_2 are the random vectors in the range of [0,1]. The alpha usually guides the pack for hunting the prey. Therefore, alpha is referred to as the

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best candidate option, whereas beta and delta gather information about probable prey locations. As a result, the first three best solutions retrieved are then saved and assessed, and the omegas or other search agents are commanded to update their current positions in accordance with the best search agent's position. These grey wolves complete the hunting process by chasing, harassing and lastly attacking the targeted prey when it stops escaping. For designing an MPPT method based on this GWO technique, we redefined the duty ratio (d) as the current position of the grey wolf. Thus, equation (5) is updated as:

$$D_i(k+1) = D_i(k) - A.E$$
 (eq. 8)

3.2 Incremental Conductance (IC) MPPT

The Incremental Conductance approach helps to track the peak point by correlating the instantaneous conductance (I/V) value of the module or array with its incremental conductance $(\Delta I/\Delta V)$ value on a continuous basis. As we know, the slope of P-V characteristic is zero at MPP, negative when operating point is at the right side of MPP, and positive when it is on the left side of MPP (Saravanan and Babu, 2016), i.e.,

$$\frac{dP}{dV} = 0, \qquad \text{at MPP}$$

$$\frac{dP}{dV} > 0, \qquad \text{left of MPP}$$

$$\frac{dP}{dV} < 0, \qquad \text{right of MPP}$$
(eq. 9)

Now, the above Eq. (9) can be represented as:

$$\frac{dP}{dV} = \frac{d(I.V)}{dV} = I + V \frac{dI}{dV} = I + V \frac{\Delta I}{\Delta V}$$
(eq. 10)

Comparing both these equations (9) and (10), Eq. (9) can be rewritten as,

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V}, \quad \text{at MPP}$$

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V}, \quad \text{left of MP}$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V}, \quad \text{right of MPP}$$
(eq. 11)

The objective of the IC algorithm is to find and select a suitable perturbation value so that incremental conductance becomes equals to the instantaneous conductance value and the PV system constantly maintains at peak operating point.

3.3 Proposed Hybrid MPPT technique

In this study the advantages of both grey wolf optimization (GWO) and incremental conductance (IC) MPPT are integrated to design a new hybrid MPPT approach so as to extract maximum possible power from an array or modules under partial shading conditions. The proposed technique, based on search and optimization approach, is intended to detect the global peak correctly and as a result, the overall performance of the PV system is improved under any environmental changes within the shortest time possible, with higher tracking speed and lower oscillations around the MPP. This method forces the GWO to operate during the initial stages for tracking the GP and the IC to operate during the final stages to locate the peak operating point by regulating the duty ratio of the converter to achieve high tracking efficiency and faster convergence rate. In this method, the duty cycle of the boost converter indicates the current position of a grey wolf. When these wolves find the GP i.e., when they reach close to each other, the IC method activates at the position of the best candidate search agent (wolf) in the GWO process. The flow-chart of the proposed Hybrid GWO-IC MPPT technique is presented in Fig 7.



Fig. 7: Flowchart of the proposed Hybrid-MPPT technique

4. Results and discussion

The block diagram of the PV system incorporated with the proposed hybrid-MPPT technique is depicted in Fig 8. The proposed technique is simulated for a 1 kWp PV system for 4S and 2S2P topologies to verify its effectiveness under rapidly varying PSCs using MATLAB/Simulink tool. The PV module chosen in this study is Tata Power Solar System TP250MBZ and its parameters under STC is presented in Table 1. The main components used in simulation are $C_{in} = 10\mu$ F, $C = 470\mu$ F, L = 1.2mH, f = 20 kHz, and $R_L = 53\Omega$ for designing the boost converter (DC-DC). The GWO-IC MPPT is compared with conventional P&O, IC and GWO based MPPT methods for evaluation of its performance.



Fig. 8: Block Diagram of Proposed Hybrid-MPPT Algorithm

Tab 1: Datasheet of the simulated PV module

Parameters	Value
Maximum power (W)	249
Open circuit voltage (V)	36.8
Short circuit current (A)	8.83
MPP voltage (V)	30
MPP current (A)	8.3
Temperature co-efficient of open circuit voltage (% / $^{\circ}$ C)	- 0.33
Temperature co-efficient of short circuit current (%/ $^{\circ}$ C)	0.0638



Fig. 9: Simulated waveforms for 4S configuration (a) STC (b)-(d) Tracking curves under PSCs

Fig 9 and 10 presents the simulated tracking waveforms of power, voltage, and current for both 4S and 2S2P configuration under PSCs considering GWO-IC, GWO, P&O, and IC methods. During the simulation of 4S configuration, shading pattern I turn up for first 0.25s and shading pattern II appears for next 0.25s. The proposed GWO-IC MPPT tracks the GP of 637.91W at 0.078s, while GWO finds the peak of 637.10W at 0.110s, IC detects the peak of 630.32W at 0.118s, and the P&O method converges to peak of 631.22W at 0.148s under shading

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Pattern-I. At time 0.25s, shading Pattern-I gets replaced by pattern-II and the MPPT algorithms restarts to track the peak operating point. Under shading pattern-II, GWO-IC locates the GP of 409.99W at 0.052s, GWO tracks the peak of 409.33W at 0.053s, while IC and P&O fails to detect GP and tracks the LP of 398.87W and 388.63W respectively at convergence time of 0.098s and 0.089s. The tracking waveforms under PSCs and STC for 4S configuration are shown in Fig 9. Similarly, for 2S2P configuration shading pattern III and IV appears for each 0.25s intervals. The assigned values of irradiance for different shading patterns are indicated in Fig 3. Under shading pattern-III, GWO-IC MPPT tracks the GP of 482.34W at 0.056s, GWO detects the peak of 480.69W at 0.094s, IC reaches the peak of 466.91W at 0.109s, and the P&O locates the peak of 474.37W at 0.156s. While, under shading pattern-IV, GWO-IC locates the GP of 587.73W at 0.043s, GWO tracks the peak of 585.91W at 0.073s, IC detects the peak of 562.56W at 0.044s, and the P&O converges to peak of 554.41W at 0.046s. The tracking waveforms under PSCs and STC for 2S2P configuration are shown in Fig 10.



(c)

(d)

Fig. 10: Simulated waveforms for 2S2P configuration (a) STC (b)-(d) Tracking curves under PSCs

Tab. 2: Performance comparison of the proposed hybrid MPPT	method for 4S configuration
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Shading pattern and Maximum power (W)	MPPT technique	PV power (W)	Convergence time (s)	Tracking efficiency (%)
	GWO-IC	637.91	0.078	99.99
Pattern I	GWO	637.10	0.110	99.86
(637.96 W)	IC	630.32	0.118	98.80
	P&O	631.22	0.148	98.94
	GWO-IC	409.99	0.052	99.95
Pattern II	GWO	409.33	0.053	99.79
(410.18 W)	IC	398.87	0.098	97.24
	P&O	388.63	0.089	94.74

Table 2 and 3 summarizes the simulated results displayed in Fig 9 and 10 respectively. It is found from these Tables that the proposed hybrid GWO-IC MPPT exhibits higher tracking efficiency (>99%), faster tracking speed
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(<0.1s), and negligible oscillations around MPP. Thus, it is clear that the GWO-IC deals with PSCs efficiently and outperforms the other MPPTs namely, P&O, IC and GWO methods. Table 4 presents the comparison between different MPPT methods with respect to convergence speed, tracking accuracy, implementation complexity, power oscillations and dynamic response. It is observed from Table 4 that the proposed method performance is much better compared to all other methods.

Shading pattern and Maximum power (W)	MPPT technique	PV power (W)	Convergence time (s)	Tracking efficiency (%)
	GWO-IC	482.34	0.056	100
Pattern III	GWO	480.69	0.094	99.65
(482.34 W)	IC	466.91	0.109	96.80
	P&O	474.37	0.156	98.34
	GWO-IC	587.73	0.043	99.99
Pattern IV	GWO	585.91	0.073	99.68
(587.79 W)	IC	562.56	0.044	95.71
	P&O	554.41	0.046	94.32

Tab. 3: Performance comparison of the proposed hybrid MPPT method for 2S2P configuration

Tab. 4: Comparison of hybrid GWO-IC MPPT with other MPPT algorithms

MPPT technique	Convergence speed	Tracking accuracy	Implementation complexity	Power oscillations	Dynamic response
P&O	Slow	Low	Simple	High	Poor
INC	Fast	Accurate	Complex	Less	Good
OCV	Slow	Low	Simple	High	Poor
SCC	Slow	Low	Simple	High	Poor
GWO	Fast	Highly accurate	Medium	Zero	Very good
GWO-IC	Very fast	Highly accurate	Medium	Zero	Very good

5. Conclusions

A hybrid GWO-IC MPPT based on grey wolf optimization and incremental conductance is proposed that can effectively track the MPP under any environmental conditions. The detailed performance comparison of GWO-IC method with the traditional MPPTs such as P&O, IC and Grey Wolf Optimization MPPT method is carried out. The comparison is done with reference to tracking efficiency, faster convergence to GP, and low oscillations around MPP for different configurations and at rapidly changing partial shading conditions. The results obtained from the simulation clearly indicate that the proposed hybrid MPPT exhibits higher tracking efficiency (>99%), faster convergence to the global peak with minimal time (<0.1s), negligible oscillations around MPP as compared to P&O, IC and GWO based MPPT technique.

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G-07. Smart Grids and Microgrids

Practical Insights for Microgrid Operation with Energy Management Capable Prosumers

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Abstract

Microgrid prosumers with distributed energy resources (DER) can participate in coordinated control strategies that benefit microgrid operation, such as reducing peak demand and improving PV hosting capacity. Recent literature presents several optimal DER management strategies considering methodologies usually based on mathematical models and simulation. This work evaluates the practical operation of two off-the-shelf bidirectional PV-battery inverters with DER management capability under different operating scenarios, accessing important practical aspects that are often ignored in the development of simulation-based strategies for energy management purposes. Devicespecific practical operation constraints are identified, and it is shown that some of them should be considered in control strategies as key parameters invariably present in DER operation. The practical evaluation shows that operation constraints based on battery voltage may reduce DER flexibility; instead, it is recommended that manufacturers consider batteries' state of charge.

Keywords: microgrid, distributed energy resources, energy management, demand response

1. Introduction

The adoption of smart microgrids in both off-grid electrification and grid-connected applications is recognized as an alternative in distribution level to improve system reliability, controllability, and economic and energy efficiency. A fundamental aspect of smart microgrids is the active operation of distributed energy resources (DER) that can participate in various control and management schemes, such as demand response, voltage regulation and peak shaving.

In specific microgrid scenarios, to ensure that DER operation contributes positively to the system, it is essential to actively control such resources in a coordinated manner, considering the several operating constraints at both DER and grid levels. For example, an inverter-based DER operation is constrained to its maximum power rating, while the distribution grid operation is constrained, among other factors, to a permissible voltage range. In this context, recent literature presents various strategies of DER management in microgrids, with scopes ranging from off-grid applications (Ramabhotla *et al.*, 2014; Suresh *et al.*, 2020) to large-scale urban area systems (Ross *et al.*, 2018; Sen and Kumar, 2018), with most of these works presenting a theoretical modeling approach that is validated by software simulation.

In practice, when it comes to small-scale DER control, there are off-the-shelf solutions that can manage different sources and loads, as is the case of hybrid inverters for PV-battery systems. Such devices are usually embedded with a set of standard operation strategies, such as peak-shaving, power-voltage and power-frequency droop logic, and battery charging cycling. Furthermore, device-specific parameters can be customized for specific control and management strategies, receiving real-time or day-ahead commands from a third-party operator (e.g., microgrid operator). Such functionalities make the adoption of optimal control strategies possible, targeting microgrid operation cost reduction while ensuring compliance to local power quality normative.

In this context, simulation-based theoretical approaches for optimal DER management strategies must consider the practical constraints that real systems and devices are subject to. Simple and practical models are always desirable as they make the development of optimal control at reduced computational cost possible. However, to make its practical implementation feasible, some constraints cannot be ignored, which inevitably add complexity to the model

and simulation process. Therefore, some simplified methodologies, though easy to implement, may have limited practical applicability.

This paper investigates key parameters that are often ignored in optimal DER energy management methodologies in smart microgrid applications. A lab-scale setup with multiple autonomous renewable energy systems is used to carry out the experimental tests (Manito *et al.*, 2017). A detailed operational evaluation of off-the-shelf smart hybrid inverters from two different manufacturers is used to identify practical operational constraints that must be considered in optimal energy management strategies, thus providing valuable perceptions for the research community in the field.

2. DER test setup description

The DER setup that was used to carry out the experiments is located in the PV Systems Laboratory, part of the Institute of Energy and Environment of the Universidade de São Paulo. The experimental microgrid structure comprises four prosumers with energy management capability, two three-phase (ST1 and ST2) and two single-phase (SM1 and SM2) systems. Each prosumer has local PV generation and battery storage, and measurement devices are also installed at the point of connection with the microgrid. Tab. 1 specifies the DER of each prosumer.

Prosumer	PV (kWp)	Storage (kWh)	Inverter (kW)	Prosumer	PV (kWp)	Storage (kWh)	Inverter (kW)
ST1	6.71	23.5	15	SM1	1.75	10.5	5.0
ST2	2.8	19.2	18	SM2	1.25	10.5	4.5

Tab. 1: Prosumer specifications.

The microgrid setup can be configured to operate in two topologies, parallel and cascaded, and be connected to two different external sources (the utility grid and a diesel genset), making it possible to evaluate different management schemes. In the parallel configuration, all prosumers are connected to a common bus bar, as shown in Fig. 1(a). In the cascaded configuration, the prosumer ST1 is connected to the main supply, and the other prosumers are seen as local loads by the ST1 system (Fig. 1(b)). The cascaded configuration makes it possible to control the voltage and frequency at the point of common coupling between the prosumers, where ST1 operates as a microgrid forming system, interfacing the microgrid with the aforementioned external sources, and the other systems are microgrid's prosumers. An industrial real-time controller (RTC), from National Instruments's CompactRIO series, is responsible for setting the topology, monitoring and controlling the operation and several parameters associated with each controllable DER (*e.g.*, current dispatch setpoints). Meters are connected at the ac-side of each inverter.



Fig. 1: Possible DER test configurations: (a) Parallel topology and (b) Cascaded topology.

The real-time controller, referred to as the Microgrid Central Controller (MGCC), hosts a Labview-based application that was developed considering the specific communication protocols associated with each inverter and its respective available monitoring and control variables. Therefore, a customized application was needed for each DER, increasing MGCC complexity and concept-to-implementation time. It is important to point out that the firmware of the tested off-the-shelf inverters was developed without compliance with DER interoperability standards, such as IEC 61850-7-420 (IEC, 2009), IEEE P2030.5 (IEEE, 2018) and SunSpec series of standards (SunSpec, 2021). The adoption of interoperability standards is key for developing scalable microgrid controllers and the adoption of practical DER

management strategies. The commercial inverters tested in this work were originally developed for off-grid electrification applications, but their main energy management functionalities related to grid-connected operation are present in their firmware, which enabled to test them in the microgrid setup depicted in Fig. 1. It is important to note that new devices developed specifically for grid-connected operation may comply with interoperability standards and are more oriented to smart energy management operation. Nonetheless, the practical considerations described in the following section hold true for the broader range of smart bidirectional inverters regarding the adequacy to simulation-based optimal energy management methodologies.

3. Real-time Tests and Results

To evaluate the real-time operation of the DER under MGCC commands and investigate the system's capacity to contribute to energy management strategies, two sets of tests were performed for a three-phase prosumer (ST2) and a single-phase prosumer (SM2), both operating in the microgrid cascaded topology. The tests were performed by the real-time adjustment of the inverter's parameters and prosumer's loads to emulate different operation conditions. The detailed procedure for each set of tests is described in the following items. The tested setpoints, such as charge and discharge current adjustments, were selected considering a set of different possibilities of energy management strategies that the devices could be submitted to in real-time or scheduled operation. The tests cover important operation modes in DER management, such as load peak shaving, grid feeding, and battery charging.

3.1. ST2 - Adjust battery charge and discharge setpoints

System ST2 is a three-phase system formed by the master-slave association of three 6 kW single-phase bidirectional inverters that share a DC bus bar rated at 48 V. It is not possible to directly control system ST2 power dispatch. Instead, the rms current must be adjusted using the parameters *max grid feeding current*, to determine the maximum current injection into the grid, and *maximum current of AC source*, that limits the current demanded from the external source. Furthermore, parameters *grid feeding allowed* and *charger allowed* are used to determine whether the system operates injecting or demanding current from the grid. Grid feeding current is constrained by parameters on both AC and DC sides. On the AC grid side, grid feeding current is limited by an increase in system frequency and voltage; on the DC side, battery voltage reduction also limits the grid feeding current parameter.

To exemplify the practical constraints associated with ST2 operation, the test results shown in Fig. 2 present the controlled dispatch by adjusting *max grid feeding current* and *maximum current of AC source* parameters, given different set points of current in both directions: microgrid-to-prosumer (positive active power) and prosumer-to-microgrid (negative active power). The test started with the battery fully charged. ST1 was disconnected from the main grid and was forming the microgrid's main AC bus bar.



Fig. 2: ST2 charge and discharge test.

In the first half of the test (regions I and II), the ST2 battery bank was discharging, injecting power into the microgrid. As the injected power increases, battery voltage drops from 55.5 V to 50.8 V in approximately 1 hour, and the last discharge setpoint, in region II, was not achieved due to battery low-voltage constraint – even though the battery state of charge was within the admissible range. Furthermore, it is observed that at the end of region II, microgrid frequency increases as a result of P-f droop control of ST1, which further reduces the power injection from ST2. In the second half of the test (regions III and IV), ST2 demanded power from the microgrid to charge the battery bank. However, the demand setpoint in region IV (1.5 kW) was not reached as the high state of charge of the battery limited the charging power. Furthermore, during the power limiting event, unbalance was observed between the three phases of the system – which is a device-specific function to improve charging efficiency.

It is important to note that the battery bank used in the test presented in Fig. 2 was at the end of its service life (low state of health), and even small variations in charge or discharge current originate large variations on the battery voltage. This is clear in Fig. 2 region I, where the voltage variation is also associated to variations in the local PV generator output current.

3.2. SM2 - Peak Shaving and Microgrid Feeding

System SM2 is a single-phase system formed by a bidirectional converter rated at 4.5 kW, connected to a 48 V battery bank. As in ST2, it is not possible to directly control its power dispatch, being the rms current the variable that can be controlled by adjusting the parameters *Load Shaving Amps* and *Maximum Sell Amps*. These parameters determine the maximum current to be demanded from the grid and the maximum current to be fed into the grid, respectively. Furthermore, parameters *Grid Support, Charger Enable/Disable* and *Sell Enable/Disable* must be set according to the desired operation. SM2's inverter operation is very sensitive to battery voltage, as indicated in Fig. 3(a).



Fig. 3: (a) Converter operation modes as a function of battery voltage. Source: Schneider (2012). (b) 12 V Lead-acid battery typical discharge curves. Source Freedom (2008).

According to the inverter's manual, if the battery voltage is above the level defined by the parameter *Grid Support Volts* the inverter is capable of operating in grid support mode, which is to provide P-f, P-V and Q-V droop curves. When the battery voltage is below that level and above the level defined by the parameter *LBCO (Low Battery Cutout)* + 2V, the inverter can operate in peak load shaving (or grid feeding) mode, with maximum grid current set by *Load Shaving Amps*, as defined before. AC PassThrough Mode, shown in Fig. 3(a), bypasses the inverter and directly connects the local loads to the grid. In Charge Mode, the bidirectional converter operates as a rectifier to charge the battery, being a load to the system. Given this sensitivity to battery voltage, it is fundamental to properly determine the parameters within brackets in Fig. 3(a) to ensure that the inverter can operate according to an optimal dispatch strategy. A restricted set of parameters may reduce operational flexibility, while a broader range may reduce battery lifetime.

However, to optimally determine those parameters is not a simple task, as the battery voltage is highly dependent not only on its state of charge but also on the discharge current. An example of this dependence is shown in Fig. 3(b) for the 12 V lead-acid battery used to form SM2's battery bank.

To exemplify the practical constraints associated to SM2 operation, two tests were performed: peak shaving and microgrid feeding. Fig. 4 presents the results for the peak shaving test for different maximum microgrid current setpoints and local SM2 load. The purple dashed line indicates the maximum microgrid current setpoint, while the

solid green line indicates the current measured at the microgrid connection point, where positive values indicate microgrid-to-SM2 power flow. It can be seen that the inverter does not follow the maximum microgrid current setpoint. Most of the time, the actual measured microgrid current is above the *Load Shave Amps* level, even though battery current responds to changes in the peak shaving parametrization, as shown in Fig. 4(b).



Fig. 4: SM2 peak shaving test. (a) AC load and grid current and (b) battery voltage and current.

Fig. 5 presents the test results for SM2 microgrid feeding operation. The red dashed line indicates the maximum microgrid feeding current setpoint, while the solid green line indicates the actual measured current at the microgrid connection point, where positive values indicate SM2-to-microgrid power flow. Fig. 5(a) shows that the device follows the microgrid feeding setpoint until 11h05, with a small error for low current levels. At 11h05, a step-change in the microgrid feeding setpoint from 5 A to 10 A triggers the AC side protection in the inverter, which changes from microgrid feeding mode to AC PassThrough mode, bypassing the inverter stage and directing the local loads supply to the AC input. The high frequency and voltage variation in the AC side, shown in Fig. 6, can explain the inverter disconnection. As the microgrid is formed by a static power converter (ST1), the AC coupling at SM2 is more susceptible to frequency and voltage variations during transients, as is the case of the abrupt change in the grid feeding setpoint.



Fig. 5: SM2 grid feeding test. (a) AC load and grid current and (b) battery voltage and current.



Fig. 6: Microgrid voltage and frequency during SM2 grid feeding test.

Fig 5(a) also shows that after five minutes the inverter reconnects and resumes microgrid-feeding operation (11h10), following the current setpoints with a small error. However, at 11h21, the inverter protection trips again, changing the operation from microgrid feeding to AC PassThrough. This time the tripping was caused by low battery voltage after a local load increase event at 11h20. In this test, the *LBCO* parameter was set to 46 V; therefore, battery voltages below 48 V (*LBCO* + 2V) disable grid feeding operation mode. Just like in the previous tripping, after a 5-minutes interval, the inverter resumes grid feeding operation as battery voltage increases, but at this time, the grid feeding current was limited to maintain the minimal allowable battery voltage level for this operation mode (48 V), thus not following the controller setpoint. As local loads reduce and controller grid feeding setpoint is set to 5 A (11h35), grid feeding operation resumes properly until a grid feeding disable command is given by the central controller at 11h45.

4. Conclusions

The experimental evaluation presented in this paper shows that energy management capable devices, particularly bidirectional PV-battery based converters, are subject to several operation constraints that highly affect system capacity to respond to an external energy management dispatch control. Furthermore, it is shown how specific parameters affect system operation for the different inverters to achieve similar tasks, highlighting the importance of interoperability standards to promote the development of scalable, plug-and-play energy management controllers.

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The ST2 test presented two important operational characteristics that may affect system performance in terms of optimal dispatch and power quality. First, dispatch constraints due to battery voltage (*i.e.*, methodologies that use battery's state-of-charge as constraint are not adequate to be applied in this specific device) and second, three-phase unbalance during power limitation in battery rectifier operation (*i.e.*, single-phase equivalent) might not be adequate to evaluate the performance of this type of system.

The SM2 peak shaving test indicates that even though this system can follow setpoint commands from the central controller, it presents an offset error that could be corrected by implementing a feedback logic in the microgrid controller. On the other hand, SM2 responds accurately to grid feeding commands as long as the operational constraints are observed. In this respect, the need to set specific battery voltage-related parameters adds complexity to the central controller parametrization, as knowledge of battery characteristics is required to determine an optimal set of parameters. In this context, if this device used the battery state of charge as a control variable, the central controller implementation could be simplified and promote scalability to different energy storage characteristics.

Even though the tests focused on steady-state system operation given real-time changes in parameters and loads, it is also important to note the dynamic implications associated with the microgrid operation when formed by a static battery-based power converter with power rating close to the DER ratings in the microgrid. During the SM2 grid feeding test, abrupt grid feeding current setpoint changes originated AC-side voltage and frequency transients that tripped DER protection. Therefore, in this system, it is good practice for the microgrid central controller to prioritize smooth changes in operation setpoints whenever possible.

It is important to notice that the practical evaluations in this work were obtained for specific devices and operating conditions; therefore, it is not possible to generalize the results for a broader range of systems. Nonetheless, the tests provide useful perceptions of general DER characteristics that can affect system performance and must be observed when developing energy management applications with third-party central control, especially in the case of microgrids with high penetration of static converter devices. Further work will be developed considering daily system operation, to access the impact of controller parametrization and DER constraints on both energy and operation costs for the microgrid.

To summarize, the practical operation insights identified in this work are as follows:

- The microgrid controller logic must comply with the DER control logic when it comes to energy storage constraints, specifically whether the DER device considers the SoC or voltage as main constrain variables;
- When developing a microgrid model, there are cases in which it may be important to consider full threephase models, as single-phase equivalents may not be adequate if three-phase DER devices operate unbalanced;
- When the microgrid-forming device is a static power converter with power ratings close to the ratings of the DER devices, dynamic constraints might affect the DER performances, such as ramp up or ramp down rates for power setpoint changes.

5. Acknowledgments

The authors would like to acknowledge Brazilian funding agency *CAPES – Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* for the financial support (process n. 88887.609816/2021-00).

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Holistic approach to develop electricity load profiles for rural offgrid communities in sub-Saharan Africa

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Abstract

Providing energy access to remote rural communities in sub-Saharan Africa (SSA) is particularly challenging in areas where grid extension is not a viable option. For these communities, electrification and the fulfillment of the UN SDG 7 can only be achieved effectively by using off-grid electricity supply systems. However, the design process of renewable energy-based mini-grids requires a holistic consideration of all electricity needs, including the electricity demand of commercial customers (productive uses) and public institutions. Furthermore, as electric cooking is increasingly becoming a viable option, each off-grid electrification project should carefully consider to which extend electricity can be used for cooking and water heating, and that consumer preferences might change over time when they experience the advantages of e-cooking devices, which can have a strong influence on the resulting electricity load profile and electricity demand. In this research article we explore the advantages of a holistic hybrid modelling approach, which includes bottom-up and top-down modelling as well as data-driven analyses, for the generation of standard load profiles (SLP) for typical consumers in rural off-grid communities in SSA. Monitoring data from the largest off-grid settlement in Namibia, *Tsumkwe*, is used for data-driven load profile generation as well as for validation within the SLP development process. Finally, the SLP can be added up in order to synthesize customised load profiles for entire off-grid settlements in SSA.

Keywords: Electricity demand assessment, electricity load profiles, standard load profile (SLP), hybrid modelling approach, electric cooking, mini-grid, rural electrification, energy access

1. Introduction

1.1. Background

The United Nations (UN) published their "2030 Agenda for Sustainable Development" in 2015. Sustainable Development Goal (SDG) 7 is intended to ensure access to affordable, reliable, sustainable, and modern energy for all humans, with a special focus on electricity. By 2018, the proportion of the global population with access to electricity reached 90%. As a result, the absolute number of people living without electricity fell below the threshold of one billion. However, the lack of electricity supply primarily affects countries in sub-Saharan Africa (SSA), where 53% of the population have no access to electricity (United Nations, 2020).

Energy poverty disproportionately concerns those living in rural communities in SSA (Louie, 2018). It has a negative impact on different areas of daily life, and the consequences can be severe. For instance, people's health is affected by air pollution when using traditional biomass for cooking and heating in inappropriate stoves. Lacking access to modern energy also reduces education and income opportunities, and is a driver for gender inequality (Bhatia and Angelou, 2015; Louie, 2018). Furthermore, lack of access to electricity prevents people from using radio, television, and internet, which results in a lack of information and makes rural areas even more isolated (Louie, 2018). To summarize, access to clean energy is essential for human, social, and economic development.

1.2. Rural electrification through solar-based mini-grids

Many studies have shown that grid connection is not feasible for a large part of remote rural communities in SSA. Hence, rural electrification via renewable energy-based off-grid electricity supply systems is required to achieve the UN SDG 7 (IEA, 2019; Williams et al., 2019; Lorenzoni et al., 2020; Scott and Coley, 2021). For most remote settlements in SSA, mini-grids based on PV are the preferred technical solution for access to

S. Kühnel et. al. / SWC 2021 / ISES Conference Proceedings (2021)

electricity due to the high and relatively consistent solar irradiation levels in these regions. Solar-based minigrids generally consist of PV modules for electricity generation, a battery energy storage system, inverters, a control/management system, and an electricity distribution system. If further electricity generators are present, e.g. wind turbines or a diesel generator, the system configuration is called a solar-hybrid mini-grid. In contrast to individual solar home systems (SHS), mini-grids can provide entire communities with a high-quality electricity supply, that is comparable to the national grid and allows for the use of powerful three-phase AC appliances. Hence, mini-grids offer great opportunities for sustained economic and social development by enabling extensive commercial activities (productive use of electricity) and effective public infrastructures and services.

Although being the least-cost option for many rural communities, isolated mini-grids naturally imply higher electricity costs for consumers compared to users that are supplied via the national electricity grid (Kühnel et al., 2020). Therefore, any off-grid electricity supply system requires a thorough planning process, including careful holistic consideration of the electricity demand of the community it is intended to serve (Williams et al., 2019; Scott and Coley, 2021). Anticipated load profiles for isolated rural communities are a critical resource in the mini-grid design process (Prinsloo et al., 2018). Therefore, the objectives of this research article are to analyse the electricity needs of rural off-grid communities in SSA, and to present a holistic procedure to generate standard electricity load profiles for typical consumers in these settlements as well as realistic load profiles for entire communities.

2. Literature review

2.1. Energy demand vs. electricity demand in remote rural communities

The energy demand of a rural community can basically be divided into three categories (Mandelli et al., 2016): energy for household basic needs, energy for community services, and energy for productive uses devoted to income generating activities.

Energy for community services	Energy for households	Energy for productive uses
Water supply, Education, Healthcare,	Lighting	Irrigation, Agriculture,
Street lighting	Electrical appliances	Crop processing
Mobile network, TV/Radio broadcasting	Space cooling and heating	Micro market, Snack bar,
Public institutions (e.g. Community centre)	Cooking and water heating	Barbershop, Tourism

Tab. 1: Categories of energy demand in remote rural communities (cf. Mandelli et al. (2016))

As outlined in Tab. 1, each of these categories consists of a variety of very different consumers with distinct and diverse energy consumption patterns, resulting in a complex composition of the community energy demand. It is important to point out here that this energy demand will only partly be covered by electricity, while other sources of energy also play a significant role in most rural communities. For example, the energy service of 'cooking and water heating' can be provided by either non-electrical appliances (such as gas burners, solar cookers, or traditional biomass cooking stoves) or by electrical appliances like hotplates and kettles. Hence, the usage patterns of (non-) electrical heating and cooking devices have a profound influence on the resulting electricity demand and electricity load profile of the respective community and, thus, need to be considered carefully (Prinsloo et al., 2016; Scott and Coley, 2021).

For example, a survey conducted by Lloyd and Cowan (2004) in an informal settlement in South Africa revealed that the average monthly energy consumption for rural households cooking with electricity is 210 kWh, compared to 150 kWh for households without electrical cooking (Prinsloo et al., 2016). A recent "feasibility study to pave the way for mass distribution of electric hotplates to rural households in Malawi" found that electric cooking accounts for about 40% of the total household electricity consumption for a middle-frequency user (approx. 50 cooking events per month), and even 79% for a high-frequency user with approx. 75 cooking events per month. These results are all the more remarkable as only one hotplate of 1,500 W was provided to the participating households, and an accompanying survey showed that this hotplate "was too small to cook all the food for a household" so that "a fire was kept going for cooking purposes as well". The average

daily hotplate consumption was found to be 1.14 kWh/d. On average, each electrical cooking event consumed 0.53 kWh and lasted for 44 minutes (Access to Energy Institute, 2021).

2.2. Determination of electricity demand and electricity load profiles for rural communities in SSA Many research articles point out that there are major challenges and uncertainties in the assessment of the electricity demand of isolated rural settlements, especially the high variability of demand and a general lack of reliable and accessible monitoring data from existing electrification projects (Prinsloo et al., 2018; Kühnel et al., 2020; Lorenzoni et al., 2020). To address these challenges and support the planning and design process of mini-grid systems, increasing research efforts have been made in recent years concerning the electricity demand, electricity load profiles, and load forecasting for rural off-grid communities in SSA and other developing countries.

Lorenzoni et al. (2020) created a database with real-world load profiles from 61 mini-grids in the global south, which is based on primary (fieldworks) and secondary (private developers, literature) data, to provide an open dataset for researchers and practitioners. After having developed a representative daily load profile for each of these settlements, these profiles were normalised to the mean hourly demand, and grouped according to similarities in their course and duration curve. A data-driven analysis performed on the profiles revealed five "archetypal load profile clusters" and four reference load profile shapes for mini-grids. Subsequently, correlations were explored between these load profile shapes, the electricity consumption, and external factors that characterise the communities, including technical, socio-economic and geographical parameters. Nevertheless, the authors consider their database and classification of load profiles only as a first step towards a comprehensive understanding of archetypal load shapes. They call for an extension of the open dataset and for further studies to assess the load demand of off-grid communities, its evolution over time, and its correlations with further community characterisation factors (Lorenzoni et al., 2020).

Kühnel et al. (2020) also emphasise the difficulties to estimate the electricity demand and load patterns of unelectrified rural off-grid communities, and criticise the absence of a database with standard load profiles for initial electrification. The authors highlight large discrepancies between survey results (before electrification) and later consumption measurements of up to 300%, and advocate the use of data-driven load profiles for future mini-grid electrification projects. In order to create a database for this purpose, and to generate reference load profiles, Kühnel et al. (2020) suggest to develop a monitoring and evaluation framework (MEF) that collects data from mini-grid operation, and makes them available on an open-source basis to all interested stakeholders. The paper also describes and analyses in detail how the electricity demand of recently electrified settlements grows over time due to economic development, leading to immigration and increased individual consumption. However, neither commercial customers nor public infrastructures are considered in the study.

Literature review also revealed that the electricity demand for cooking and water heating is usually not (explicitly) considered in the demand assessment for mini-grid systems, despite its immense importance (see chapter 2.1). However, electric cooking is rapidly becoming a viable solution in rural off-grid areas that are powered by mini-grids, due to significant decreases in both PV and battery prices (Couture et al., 2019). Hence, the interplay between mini-grids and electric cooking has recently gained increased attention. For example, Lombardi et al. (2019) conducted an assessment of the techno-economic potential of a fully-renewable solar mini-grid for electricity load and electric cooking in community and household applications. Keddar et al. (2020) analyse the optimal sizing of mini-grids that are able to accommodate new e-cooking demand.

2.3. Generation of electricity load profiles for typical consumers in rural communities in SSA

In a scoping exercise, Prinsloo et al. (2016) identified hourly reference load profiles for both electric and thermal energy demand for typical homesteads in isolated rural African villages. These profiles are made available as a digital timeseries and can be fed directly into standard simulation software. However, this study makes the simplified assumption that a single homestead has the same archetypal reference shape like an entire village, which means that the influence of balancing effects was completely neglected.

Scott and Coley (2021) characterise household demands based on consumption and customer data of two minigrids in Tanzania. Patterns of use are analysed by examining the electrical equipment owned and the demography of supplied households. The authors identified four distinct use patterns, but also illustrate that a connection between these, the device possession and its use as well as the socio-economic status is complex to identify and call for further research.

Li et al. (2018) from the National Renewable Energy Laboratory (NREL) developed a tool named Microgrid Load Profile Explorer that allows researchers to synthesize load profiles for households and commercial users in SSA. However, the tool lacks flexibility, for example, it is based on seven appliances which are assumed to be the same for all types of households. Also, the time of energy consumption is pre-defined in the tool and there is no provision to alter it. Other shortcomings are that all types of households show a similar electricity consumption pattern, and a similar consumption trend on weekdays and weekends.

A recent study from Asuamah et al. (2021) presents a large set of daily load curves that are developed on the basis of a survey analysis. The estimation of energy demand is categorised into three areas (residential users, commercial users, and street lighting), with the residential users being sub-classified in low-, middle- and high-class users. Similarly, the commercial load is differentiated into small-, medium and high-scale users.

2.4. Electricity load profile modelling approaches

A comprehensive review of 32 residential electricity load profile models and the underlying modelling techniques is given in Proedrou (2021). At present, load profile models are typically categorised as top-down and bottom-up models. However, in recent years new models have been developed that do not fit into either category as they combine methods and elements of both the top-down and bottom-up approaches. Consequently, Proedrou (2021) proposes to introduce a new sub-category of "hybrid models" for this novel modelling approach.

Besides the basic modelling technique, electricity load profile models can also be classified according to their primary intended application. As there is no generally accepted classification scheme, Proedrou (2021) suggests a division into three areas of application: (a) demand side management (DSM), (b) planning, control and design of energy systems, distributions grids and local energy efficiency strategies (PCD), and (c) residential load profiles (RLP). Furthermore, load profile models can be differentiated based on their sampling rate – low-resolution models (15 minutes to 1 hour), middle-resolution models and high-resolution models (sampling rate of at least 1 minute) – as well as based on the main statistical methods that are used in the modelling process: Markov chain models, probabilistic models, and Monte Carlo models (Proedrou, 2021).

However, the 32 residential electricity load profile models reviewed in Proedrou (2021) cannot be used for the purpose of this research article – the development of standard electricity load profiles for typical consumers and entire off-grid settlements in rural SSA – as these models are tailored to the residential sector in developed countries and require input data that is not available for rural communities in SSA. Also, the 30 publicly available residential load profiles, that are presented in Proedrou (2021), do not apply to the aforementioned objective as these existing datasets refer to developed countries or, in case of the "Indian data for Ambient Water and Electricity Sensing" (iAWE), to a three-storey home in the city of Delhi (Batra et al., 2013).

3. Holistic approach to generate standard electricity load profiles for typical consumers in rural off-grid communities in SSA

The extensive literature review revealed that there is no standardised method for assessing the electricity demand and electricity load profiles, respectively, of rural off-grid settlements in SSA. Load assessment remains a complex task, which is particularly critical for currently un-electrified communities. However, existing mini-grids are also continuously exposed to on-going changes of electricity demand, be it through demographic changes, or due to the adoption of new technologies such as electric cooking and water heating, and potentially also electric vehicles. In particular, the electricity demand for cooking and water heating is not (adequately) considered in many load profiling models and tools, although it can have a very significant influence on the community load profile already today, and will become even more important in the future.

In conclusion, all existing approaches to anticipate the load characteristics of rural communities in SSA, that are known to the authors, have shortcomings in one way or another. Therefore, this paper aims to contribute to reducing this information gap by presenting a holistic procedure for the development of standard load profiles (SLP) for typical consumers in rural off-grid settlements in SSA. In this research article, the term 'SLP' refers to a load profile that represents the average electricity demand curve of a specific consumer type, similar to the well-known H0 SLP for European households (cf. Proedrou (2021)). The fundamental advantage

of SLP is their additivity, i.e. their suitability to be added up directly in order to determine the load profile of a group of consumers or an entire community.

The ultimate goal is to model the electricity load profile of entire off-grid settlements that are currently unelectrified. For this purpose, validated SLP are combined with information about the structural composition of the target community: structural data, such as the number of households and information about the public infrastructure, are used to determine a set of SLP that represent this specific settlement as a whole. Finally, these SLP are added up to the settlement load profile, which in turn can be used to custom design a mini-grid.

To achieve these goals, a holistic hybrid load profile modelling approach is proposed in this study. As shown in Fig. 1, we suggest to combine bottom-up and top-down modelling as well as data-driven load profile generation techniques, in order to compute generally applicable SLP for typical consumers in rural off-grid communities in SSA. According to the classification of load profile models proposed by Proedrou (2021), our modelling approach can be characterised as a hybrid low-resolution model for the purpose of PCD (planning, control and design of energy systems and distributions grids) and using probabilistic statistics (see section 2.4).



Fig. 1: Holistic approach for the development of standard load profiles for rural off-grid communities in SSA

3.1. Bottom-up modelling

A general description of the bottom-up modelling method to develop household load profiles is given in Proedrou (2021) and Gao et al. (2018). In this paper, the bottom-up modelling process starts with the definition of consumer types as indicated in Fig. 1. Every consumer type is characterized by a set of electrical appliances – including the type, quantity, and power rating of each appliance – and the typical usage pattern (operating times) of these appliances. Typical examples for consumer types from the residential, commercial, and public sectors are a middle-income household, a snack bar, and a primary school.

Subsequently, sub-types are created in order to generate a large set of electricity load profiles for each consumer type. Different consumer sub-types account for differences in the use of electrical appliances (different user behaviours). They also allow for modelling slight variations in appliance possession, for example, a small household is likely to have fewer lights and mobile chargers than a large household of the same income level. The effects of the creation of consumer sub-types are demonstrated in more detail in section 4.1. Furthermore, for the majority of consumers, it is not sufficient to develop a general set of daily load profiles. Instead, there are regular load variations that occur in the course of the year. Most important for most consumer types are the changes between weekdays and weekend days. Therefore, specific load profiles are generated for weekend days – in some cases it is also necessary to differentiate between Saturday and Sunday – which finally allow the construction of weekly load profiles.

Moreover, some consumer types require a careful consideration of seasonal variations. For example, the cooling demand (during sunshine hours) and the heating demand (during night hours) of households can change considerably in the course of the year. In rural Namibia, the electricity use for cooking is much higher on rainy days compared to dry and sunny days, on which traditional cooking with biomass is preferred. Last

but not least, the recurring changes between school periods and holiday periods result in extreme differences for the daily electricity demand of any school.

The result from our bottom-up modelling procedure is a set of synthetic load profiles for each consumer type, which cover a large range of user behaviours and differences in appliance possession, as well as changes in electricity demand in the course of the year. The great benefit of synthetic load profiles is that they indicate the peak load of a consumer. As shown in Fig. 1, the synthetic load profiles are fed into the hybrid load profile model in order to be validated and transformed into SLP.

3.2. Data-driven load profile generation

As described in sections 2.2 and 2.3, the availability of monitoring data from rural electrification projects in SSA has increased in recent years. This treasure trove of data is increasingly being analysed by researchers, and used to generate data-driven load profiles and for load forecasting. In the future, if high-resolution measurement data will become available as well, also highly sophisticated methods of data analysis could be applied, such as time series analysis, load disaggregation via non-intrusive load monitoring (NILM), and machine learning. The data-driven approach can also be combined with bottom-up modelling for the purpose of electric load forecasting (Ye et al., 2019), and provide valuable input for top-down modelling and the top-down analysis of measurement data (see Fig. 1).

3.3. Top-down modelling and top-down analysis

Top-down models use historical data at an aggregate level and/or statistical parameters "to derive relationships between them and the electricity consumption" (Proedrou, 2021). For this reason, these models are also referred to as statistical models (Gao et al., 2018), and the data-driven classification and load profile modelling approach proposed by Lorenzoni et al. (2020), using characterisation factors, falls under this category.

A basic principle of top-down analysis is to break down aggregated data into sub-categories, and into shorter time periods. For example, in the first step, the electricity consumption at community level can be sub-divided into the main consumption sectors of an off-grid community: the residential, commercial and public sector (cf. Fig. 1 and Tab. 1). Similarly, the annual electricity consumption can be disaggregated into the electricity consumption per month. This step makes it possible to examine the seasonal variations of the electricity demand of a particular community, and to relate them with the seasonal changes in the availability of renewable energy resources (e.g. solar irradiation) in this settlement.

In the next step, if sufficient information is available, the electricity demand is further divided into groups of consumers (e.g. a district/neighbourhood), and finally into single consumers. When the monthly electricity consumption is broken down further into daily consumption figures, recurring changes in the course of the week can be detected and incorporated into the top-down model (e.g. weekday-to-weekend variation). The daily consumption figures – or even hourly values – might be obtained directly from a monitoring system or from aggregating high-resolution monitoring data (see Fig. 1).

Finally, the electricity consumption figures can be evaluated statistically in order to recognise and quantify major correlations and influencing factors. Further insights are gained by calculating statistical parameters such as the average or median daily/weekly/monthly electricity consumption of the households in a settlement. These statistical key figures are also a valuable input for the development and validation of SLP in hybrid load profile modelling (see Fig. 1). Last but not least, histograms and other statistical diagrams can provide a deeper understanding of the electricity demand structure in a particular community in SSA.

3.4. Hybrid load profile modelling

In general, the hybrid load profile modelling approach is a combination of bottom-up and top-down modelling (Proedrou, 2021). However, due to the general shortage of reliable information and measurement data from off-grid settlements in SSA, we propose to combine all available pieces of information in a holistic hybrid modelling procedure (see Fig. 1). This includes a comprehensive set of synthetic and data-driven load profiles, as well as electricity consumption figures and statistical parameters from top-down analysis and literature (e.g. energy statistics and real-world monitoring data). In an iterative process, the raw load profiles are validated and SLP are developed for typical consumer types in remote rural communities in SSA.

This validation includes a check and calibration of the (raw) synthetic load profiles with verified electricity consumption figures (e.g. kWh/d). After validation, the resulting load profiles (which are meant to represent the *course of electric load of an individual consumer* as accurately as possible) are transformed into SLP, which are intended to represent the *average expected load curve for a large number of consumers* of the respective consumer type.

Hence, SLP are intended to be additive and generally applicable for load assessment and load forecasting. SLP cover the same amount of electricity (in kWh/d) as individual load profiles, but have a strongly smoothed curve shape. Furthermore, while individual profiles show the true height and width of consumption peaks, SLP have significantly flatter and wider peaks.

4. Results and discussion

In this section, the development of synthetic load profiles and data-driven load profiles is demonstrated at the example of *Tsumkwe*, a rural off-grid settlement in the Otjozondjupa region in the north-east of Namibia. *Tsumkwe* has the largest solar-hybrid mini-grid system in Namibia and is analysed as one of the case studies within the *PROCEED* research project¹. The *Tsumkwe Energy Project (TEP)* was initiated in 2011 and transformed the existing diesel-powered mini-grid into a solar-diesel hybrid mini-grid. Besides the integration of a PV plant and a battery bank into the electricity supply system, the *TEP* also introduced extensive electricity saving measures in the settlement of *Tsumkwe*: electric water heaters and electric stoves were replaced by solar water heaters and LPG stoves, and inefficient incandescent lights were exchanged for energy saving lights.

4.1. Bottom-up modelling: Household load profiles

In this study, the households of a rural community are categorized into three consumer types: (i) low-income, (ii) middle-income, and (iii) high-income households. As described in section 3.1, each of these household types is characterized by a representative set of electrical appliances and their typical times of use.

In order to consider the differences in appliance possession and appliance usage patterns within a specific consumer type, each household type is further divided into different household sub-types. For example, we differentiate into small (1-5 persons), medium (6-10 persons), and large (>10 persons) households. For each of these sub-types, Tab. 2 shows the respective set of appliances that are typically used by a middle-income household in a Namibian rural off-grid settlement such as *Tsumkwe*. This information is based on surveys and observations from research stays within the *PROCEED* project, and was cross-checked by the *Namibia Energy Institute* and engineers from *DIS Engineering*, a solar company that has recently implemented a solar PV installation in *Tsumkwe*.

Appliance	Power rating	Quantity		
	Watts	1-5 persons	6-10 persons	10+ persons
CFL Bulb	8-12	2	4	6
Mobile Phone Charger	10-15	2	3	4
Radio	10	1	1	2
TV	150	1	1	1
Satellite Dish + Decoder	40	1	1	1
DVD Player	20	1	1	1
Small Fridge	250	1	1	1
Laptop	65	-	-	1
Electric Hot Plates	1000	2	2	4

Tab. 2: Typical sets of electrical appliances for middle-income households of different sizes in Tsumkwe

¹ Pathway to Renewable Off-Grid Community Energy for Development. <u>https://www.bmbf-client.de/en/projects/proceed</u>

In the following, we demonstrate the bottom-up modelling procedure and present preliminary results for a medium-sized (6-10 persons) middle-income household. Fig. 2 shows the preliminary synthetic load profile of this household sub-type for a working day with electrical cooking. Although the residents in rural off-grid communities generally use relatively old and inefficient electrical appliances, the load profile is dominated by the electricity demand of the hot plates. If cooking is not done electrically, the load profile is dominated by the fridge and the TV. When different household sizes are compared, the most noticeable difference on days with electrical cooking is the almost doubled peak load for large households due to the double number of electric hot plates.



Fig. 2: Preliminary synthetic load profile of a medium-sized (6-10 persons) middle-income household in *Tsumkwe* with electrical cooking on a working day (left). Comparison of synthetic load profiles of middle-income households of different sizes (right)

In reality, even households with the same number of residents and an identical set of appliances will use their electrical appliances in a different way. Moreover, even in a specific household the time and duration of appliance use differ from day to day. In order to deal with these variations in user behaviour, which represent a major uncertainty in bottom-up modelling, three different load profiles for each consumer sub-type are generated: besides the profiles presented in Fig. 2, which refer to an average appliance use, we also generate a profile for a lower usage and a profile for higher appliance usage, respectively. This procedure results in a range in which the electric load can be expected (see Fig. 3). This increase in variety and flexibility is also a benefit for subsequent modelling steps, namely for the validation of synthetic load profiles and the development of SLP (see Fig. 1). Fig. 3 also shows the differences in electric load between weekdays and weekend days. On the weekend, a typical household has a shifted morning peak and a higher electricity demand during the afternoon and evening hours.



Fig. 3: Assumed variations on the synthetic load profile of a medium-sized middle-income household with electrical cooking in *Tsumkwe* due to different intensities of appliance usage (left) and the weekend effect (right)

Fig. 4 shows the full range of electrical load that is expected, under the assumptions made in this study, for a middle-income household in a rural off-grid settlement on a working day if electric cooking is used. The lower boundary of this range is formed by the synthetic load profile of a small (1-5 persons) household, which has a lower appliance use than the average 1-5-person household. Similarly, on the upper side, the range is limited by a large household (more than 10 members), which uses more electricity than other households of this size, including a third meal that is prepared on the electric hot plates during noon hours.



Fig. 4: Full range of electric loads (grey area) that is covered by the synthetic load profiles for all sub-types of a middle-income household with electrical cooking on a workday in a rural off-grid settlement such as *Tsumkwe*

4.2. Data-driven load profile generation: Electricity load profiles of a boarding school

In this section, the development of data-driven load profiles is demonstrated at the example of the secondary school in *Tsumkwe*. This school is a boarding school complex and consists of the classroom building, a boarding home for students (including a kitchen and a cold storage room), and teachers' houses. For the school complex as a whole, there are monitoring data available for the entire year 2020 as shown in Fig. 5. This dataset was collected within the *PROCEED* project and represents 15-minute averages of the electric load (or: power consumption).



Fig. 5: Electric load patterns of the secondary school complex in Tsumkwe

As a first step of load profile development, the year 2020 is divided into four characteristic periods of school operation as shown in Fig. 5 (the first days and the last days of the year, which are not assigned to any period, are the summer holidays). Subsequently, each of these periods is evaluated individually in order to generate meaningful data-driven load profiles that are representative for specific modes of school operation. Also within each period, we carefully select a representative data set for evaluation. For example, when computing the load profile of a typical school day (cf. Fig. 6), the weekend days are removed from the data set in a first step. Secondly, every public holiday is excluded from the representative data set of school days, and data gaps are eliminated.



Fig. 6: Electricity load profile of the secondary school complex in *Tsumkwe* on a school day (regular schooling before the COVID-19 pandemic)

Fig. 6 shows the final representative dataset, which was used to compute a representative data-driven load profile for school days of the regular schooling period in 2020 before the COVID-19 pandemic, with each red dot representing a measured 15-min average electric load of the *Tsumkwe* secondary school complex. This specific data set contains all workdays (Monday to Friday) from 03-02-2020 to 13-03-2020, i.e. 30 days of regular school operation. Finally, the mean value is calculated from all load values with the same timestamp. This results in four average electric load values for each hour of the day, which are plotted as the blue line in Fig. 6 and represent the data-driven school day load profile of the aforementioned period.



Fig. 7: Electricity load profiles of the secondary school complex in Tsumkwe

Fig. 7 shows the data-driven load profiles of all three major schooling periods that are indicated in Fig. 5, together with a data-driven load profile derived from the regular school days in February/March 2021. It is noticeable that the average electric load and, thus, electricity consumption is significantly higher after the COVID-19 break and the subsequent reduced schooling phase, than before the COVID-19 upheavals. Secondly, the load profiles presented in Fig. 7, together with on-site information from *Tsumkwe*, indicate that thermal needs primarily shape the load profiles of the school complex: the particularly high electric loads measured in the evening hours can primarily be attributed to the teachers' cooking activities, the prominent morning peak in the regular schooling period before the COVID-19 break occurs mainly due to the preparation of breakfast, and the high baseload at night is mainly caused by the cold storage room. Last but not least, the electricity load profile derived from the period of reduced schooling after the COVID-19 break (depicted in red in Fig. 7), is characteristic for a non-boarding school without breakfast preparation before school starts.

4.3. Top-down modelling: Electricity consumption by sector

As outlined in section 3.3 and Fig. 1, the first step of top-down modelling is to disaggregate the overall electricity consumption of an off-grid community into the main consumption sectors: the residential, commercial, and public sector. For the settlement of *Tsumkwe*, this breakdown is performed based on the energy sales report 2020/21 (July 2020 - June 2021), which was made available by the local mini-grid operator *CENORED* (*Central North Regional Electricity Distributor*):



Fig. 8: Disaggregation of the total electricity consumption of the *Tsumkwe* settlement into the main consumption sectors (preliminary results)

However, the results shown in Fig. 8 need to be regarded as preliminary results and treated with caution, due to three reasons: (i) the data set is incomplete (August, September), (ii) the exact distinction between the business sector and the public sector is unclear, and (iii) the underlying accounting period was strongly influenced by the COVID-19 pandemic. Therefore, the breakdown into consumption sectors shown in Fig. 8 still needs to be validated and is primarily intended to illustrate the top-down analysis approach in general.

5. Conclusions and Outlook

Solar-based mini-grids can make an essential and effective contribution to achieving universal access to electricity as formulated in UN's SDG 7. However, reliable electricity load profiles remain a critical resource for the proper design of mini-grids for un-electrified rural communities in SSA. As a contribution to reduce this information gap, our article proposes a holistic approach to develop standard load profiles (SLP) for typical consumers, and to forecast electric load profiles for entire off-grid settlements of different sizes and structures. These load profiles are intended to simplify and accelerate the design process for new mini-grids, by dispensing with detailed and time-consuming on-site surveys.

The term 'holistic' has a threefold meaning in this paper, referring to (i) the integration of all available pieces of information from bottom-up and top-down modelling as well as data-driven analyses, (ii) an explicit consideration of the electricity demand of productive uses (commercial sector) and community services (public sector), and (iii) a careful consideration of the thermal energy needs, which can be provided either by electrical

or by non-electrical devices (e.g. gas burners, solar thermal systems, solar cookers, and traditional biomass stoves).

The question whether – and to which extent – electrical appliances are used for cooking, water heating/boiling and cooling has a strong influence on the electricity load profile and the resulting electricity demand, both at individual consumer level and community level. In rural Namibia, the actual use of electrical devices for thermal services heavily depends on the current weather conditions. For example, electrical hot plates and kettles are used more likely and more intensively on rainy days because the use of wood burning stoves and solar-based devices is considerably lower on these days. As the increased electricity consumption for thermal services overcompensates the reduced use of electrical cooling devices (mainly fans), the electricity demand is especially high on rainy days with a particularly low solar radiation supply. Nevertheless, the influence of thermal needs, and of electrical appliances to meet these needs, is usually not addressed in the literature on electricity load profiles and electricity demand assessment in the context of rural off-grid settlements in SSA.

As highlighted in Kühnel et al. (2020), especially renewable energy-based mini-grids are vulnerable to growing electricity demand over time. Therefore, a holistic modelling approach should also allow for modelling the evolution of electricity demand due to a growing population and increased individual demand. For the modelling procedure proposed in this study, this basic requirement is ensured by the fact that settlement load profiles can be synthesized from SLP of individual consumers. Hence, the number of SLP can be easily increased in order to represent an enlarged community. Secondly, growing individual demand (due to greater appliance possession and/or more intensive appliance use) can be considered either by adapting the SLP of the respective consumers, or by creating new SLP for new consumer types.

This modularity and adaptability are key advantages over the approaches presented in section 2.2, which model the settlement load profile as a whole (cf. the concept of "archetypal profiles" in Lorenzoni et al. (2020)). The inherent flexibility of our holistic modelling approach also allows investigating the influence of new consumers on the settlement load profile, e.g. the connection of new households to the mini-grid, the opening of new businesses, or the purchase of new electrical consumers such as electric vehicles, which increasingly plays a role in electrified rural off-grid communities. Also, potentially changing practices regarding the use of electrical appliances for cooking and water heating can have a major impact on the evolution of the electricity demand of an electrified community, and should therefore be examined more closely.

Based on the holistic modelling approach described in this research article, SLP need to be developed for typical consumer types in rural off-grid communities in SSA. For the validation step within the SLP development process, current monitoring data is available for selected consumers in the mini-grid settlements of *Tsumkwe* and *Gam*, including different types of households, a clinic, a lodge, and a police station. For both mini-grid communities, which are located in the Otjozondjupa region in the north-east of Namibia, further onsite information is available, such as socio-geographical and socio-economic data, including survey results. The validated SLP will be made publicly available in an online database to the research community and to practitioners working in the field of mini-grid planning and development. This tool is expected to facilitate the generation of customised load profiles for off-grid settlements in SSA.

6. Acknowledgments

This research was funded by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany within the CLIENT II funding programme "International Partnerships for Sustainable Innovations" under the project "*PROCEED*" (Project ID 03SF0570A-D). The authors highly acknowledge the support and contribution of all Namibian project partners, namely the Namibia Energy Institute (NEI) of the Namibia University of Science and Technology (NUST), the Central North Regional Electricity Distributor (CENORED) as well as the Namibian Ministry of Mines and Energy (MME) for intense scientific discussion and their ongoing support for the project.

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Artificial Intelligence Assisted Smart Photovoltaics

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Abstract

The paper discusses research efforts in combining recent progress in Artificial Intelligence with automated management of solar energy generated in grid-connected photovoltaic (PV) systems along with their operationand-maintenance (O&M) and their smart on-grid integration control. The outlined research aligns with the strategy of the European Union joining Digital and Green agendas as two major pillars for the COVID-19 economic recovery in the EU and is a part of the EU funded standardization action under the H2020 StandICT programme coordinated by the author and hosted by the Smart Energy Standards Group of the European Information Technologies Certification Institute (EITCI SESG) in cooperation with the European Solar Network. It also contributes to one of the four primary objectives of the European Green Deal, i.e. to achieve a fully integrated, interconnected and digitalized EU energy market by increasing research oriented towards technical reference standardization aimed at consolidation of the expert community and the technology uptake.

Keywords: Smart PV, AI, Photovoltaics, Smart grids, Smart metering, Smart energy, MPPT, Standardization

1. Introduction

A grid-connected PV system is generating electricity from the solar irradiation while being interconnected to the utility electric power grid. It generally consists of solar panels (PV modules), inverters, power conditioning units and grid connection equipment. Such PV systems range from small residential and commercial rooftop installations to large industrial-scale solar power-plants. Unlike stand-alone (off-grid) PV power systems, a grid-connected system does not have to include integrated batteries. Thus whenever the solar irradiation conditions admit it, the grid-connected PV system automatically supplies the excess power beyond consumption by the connected load, to the utility electric grid, turning a consumer into a prosumer, thus transforming the energy market to a highly distributed model and introducing a dual concept of Distributed / Renewable Energy Sources (DES/RES). Increasing automation of the PV solar power generated in-grid feeding control, operative optimization and maintenance has been recently dubbed smart PV, although in terms of in-grid feeding control it is mainly based on the developments of the smart grid achievements. The paper studies progress on research results in this area enabling undertaking and advancing international standardization efforts regarding PV systems grid-integration, as well as pronounces the need for extending these technical reference standards towards Artificial Intelligence assisted smart control over PV systems in solar power plants, PV integrated industrial buildings and the prosumer residential homes PV installations. A progress towards AI assisted smart PV systems in Deep Machine Learning and Neural Network models trained on a feedback loop of operational parameters for O&M and the in-grid (smart grid) power feeding is expected to contribute to increasing the solar energy uptake rates in parallel to continuously impressive PV modules efficiency-to-cost ratios growth.

2. Al assisted smart PV modules research and standardization

Magnitude of various PV modules and inverters equipment producers develop their own systems of automated O&M and control processes. Many solar modules producers embed electronics into PV modules. Such systems (smart modules) enable maximum power point tracking (MPPT) along with monitoring of performance data for fault detection at a module level (cf. Dhoke, 2019). Some of these systems make use of power optimizers to maximize generated power outputs. With recent PV advancements the related electronics with a proper analytical software can compensate e.g. for shadows falling partially on a section of a solar module causing drop of electrical output of one or more strings of cells, but not zeroing the output of the entire module. A smart PV system should automatically control all its sophisticated operation parameters, including central or module-level MPPT, discover, diagnose and neutralize faults, hence improving its total efficiency, lowering

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O&M costs and increasing revenues. Main features of smart PV systems are automation, digitization and intelligence, optimally based on latest developments in AI applications (neural-networks big data learning comprising constant feedback input of all operational parameters of PV systems and their on-grid interconnection to AI enabled management system). The presented research aims at supporting international standardization efforts at a higher level of abstraction for the state of the art framework standard for deeplearning NN AI assisted smart control over PV systems in solar power plants, PV integrated industrial buildings and the prosumer residential homes PV installations. Under the StandICT H2020 supported effort, researched multitudes of possible solutions and architectures are currently evaluated in order to propose a European framework of Smart PV reference standards under a newly organized Standards Developing Workgroup hosted by the European IT Certification Institute jointly with the European Solar Network. The project is tasked by the StandICT programme to conceive 2 Request for Comments standards drafts that will be iterated among WG experts and disseminated to other international SDOs active in the area of Smart Grids and Smart Metering standards with a focus on the solar power. The newly proposed Smart PV standard aims at systemizing conceptual architecture and implementation specification to define compatibility requirements between interfaces of PV modules and their associated electronic equipment control systems with inclusion of AI and cloud technologies. It aims in filling gaps in general smart-grid uniform communication standards mainly pursued by international SDOs in this field. The relevance of this research and standardization effort is in a direct correspondence with the EU Rolling-Plan 2020 for smart energy standardization overviewing the needs for digital standards in support of the EU policy for Smart Grids and Smart Metering in focus on the PV solar energy. Accordingly with the EU Rolling-Plan 2020 ICT standards in energy are expected to cover smart grid management, grid-balancing and interfacing with millions of new renewable sources in particular optimizing efficiency in complex processes of renewable energy systems control. These standards mainly focus on uniform communication and cybersecurity protocols (providing plug & play compatibility for new devices entering the grid, from renewable sources to electric cars or other smart devices and IoT enhancing smart homes, buildings or cities of the future). The current dynamic EU energy transformation is driven by two main factors: the energy systems becoming clean (i.e. environmentally neutral accordingly with goals of the EU climate and energy framework and the European Green Deal strategy of the European Commission) based on renewable and consumer-centric sources, primarily in a form of the solar power, and the ongoing digital/smart transformation of the energy and electrical grid sectors. The first factor is due to the EU energy policy encouraging stakeholders to adapt to an increasing number of means of generating electricity from a variety of renewable energy sources with minimizing environmental impact (clean energy transformation). The key policy milestones for this transformation are the EU's energy and climate targets for 2030 which emphasize Europe's leading role in the global fight against climate change. These 2030 EU climate and energy framework targets include at least 40% EU domestic reduction in greenhouse gas emissions compared to 1990 (with an increased ambition to 55% reduction as a part of the European Green Deal of September 2020), at least 32% share of renewable energy consumed in the EU, at least 32,5% improvement of energy efficiency and an electricity interconnection targeted at 15%. In this context both the PV systems and the electricity networks are of key importance. In 2012 electricity represented 22% of the EU's energy consumption with renewables accounting for a share of 24% of gross production (with ca. 3% increase on 2011, while reaching as high as 30.2% in 2016 and expected to grow up to 55% in 2030, correspondingly with the 2030 energy and climate goals and the Paris Agreement). As 2020 marked a hallmark achievement in the EU (cf. Rządkowska, A., October 2020) - for the first time the electricity generation mix has been dominated by renewables (at 39% share, exceeding by 4% the combined fossil fuels at 36% of electricity generation – as confirmed by the Directorate-General for Energy of the European Commission Communication of 9th April 2021) and the solar energy steadily increasing its stake (to 5.2% on the EU-27 level, and almost up to 10% in Italy, Greece, Germany and Spain), the smart PV based contribution to its efficiency is becoming even more so important. Furthermore the consumer position in the energy value chain has considerably changed. The energy consumer can now easily become a prosumer, deploying grid-connected renewable energy source (e.g. a PV system DES/RES), feeding the surplus of the generated energy into the utility grid. For this end with smart optimization of energy efficiency the digital and energy technologies need to overlap taking advantage of most recent developments in big data enabled AI control methods, smart homes and cities applications, energy intelligent products, the IoT, 5G networks, etc. It is for a reason that the EU COVID-19 strategic response is summarized in prioritizing two pillars: the single energy market and the digital single market combined as strongly interdependent and being both critical to the policy of the EU. This is where the second factor of EU

energy transformation through smart (AI assisted) digitization is pronounced, with digital and AI holding a potential to further support uptake of the solar power. Discussed efforts target a specific sector of this outlined in-demand technical standards of smart PV systems assisted by feedback loop trained neural networks based AI. An important concept for the proposed standards is defining a common cloud-based platform specification for distributed Smart PV operational data aggregation that will enable NN deep-learning not only on individual operative systems but also on the whole ecosystem of AI enabled PV devices (with properly addressed security and privacy issues).

3. Current progress in smart energy and smart grids standardization

Initiatives at standardizing concepts and technological approaches in leveraging AI methods to enable development of disruptive solutions in PV value chain, forming cooperative relations between individual experts in both fields of AI and solar energy, as well as scaling this cooperation to the level of institutional partnerships of research and industry stakeholders, will certainly speed uptake of the AI assisted smart PV. Stakeholders of potential interest in this regard (beyond international Standards Developing Organizations) include PV systems producers (from designs to manufacturing of single solar cells up to integration of solar modules and electronic systems), PV integrators and deployments companies, operators or owners of PV power plants, as well as AI and PV industrial experts and researchers can cooperate exchanging supplied necessary data and solar subject matter expertise with AI and ML expertise. The general goal of AI assisted PV technology is in improving economic feasibility of the PV energy transition (e.g. by cost optimization of deployments and operations of solar modules), as well as increasing reliability and value of solar PV technologies upon their integration with advancing smart grids, enabling a shift of the energy market from a centralized model to a distributed one, with inclusion of prosumers in PV solar power enabled microgeneration. AI and ML hold a potential to tackle emerging challenges for the PV wide scale adoption. Naturally an ongoing identification of new applications advancing early-stage AI assisted PV technology will be taking place and the current initial standard drafting aims at tidying up technical directions of currently known applications and classifying many various approaches. The current initiation of a general level reference standard will be further iterated towards more mature and advanced technical reference standard, and to this the AI Smart PV group under the Smart Energy Standardization Group of the EITCI Institute has been established. These AI assisted smart PV standardization efforts are contextualized in following preceding initiatives. In October of 2014 the CEN/CENELEC/ETSI's Smart Grid Coordination Group (SG-CG) successfully completed requirements of the EC M/490 mandate, with industry representatives confirming their will to take over and implement the results of the Expert-Group-1 work on the first iteration of the Smart Grid standards. Consequently, EG1 of the Smart Grids Task Force assessed in 2016 the interoperability, standards and functionalities applied in the large scale roll out of smart-energy metering in Member States and in particular the status of implementation of the required standardized interfaces, along with EC recommended functionalities related to the provision of information to consumers (summarizing report was published in October of 2015). Further coordination of standardization efforts related to Smart Meters was due to the Smart Meters Coordination Group (SM-CG) established under the M/441 mandate. The SM-CG has returned the reference architecture (TR-50572) and an overview of technical requirements, continuing to liaise with its successor CG-SEG (since end of 2016, the CEN-CENELEC-ETSI Smart Energy Grid Coordination Group took over and cooperates with the EC-SGTF). In September 2017 EC issued a proposal for a regulation on ENISA on Cybersecurity certification (Cybersecurity Act) as a voluntary mechanism framework enabling creation of individual EU-wide certification schemes (with a scheme indicating a specific product/service, an assurance level and a standard for evaluation). Such schemes are now developed to verify security properties of digital energy systems. The EC fostered conceiving a common interoperability language SAREF - a standard of ETSI and OneM2M. The CEN-CENELEC-ETSI is endowed to further align SAREF with the data models developed at ISO and IEC. These are initial steps to enable smart-energy grid and its adaptive demand-response operation mode. The standards of the discussed research will mainly provide an added value as extensions of the CENELEC / IEC-TC CLC/TC-82 (Solar photovoltaic energy systems) and the CLC/TC-57 (Power systems management and associated information exchange) for power systems control equipment and systems including EMS (Energy Management Systems) and SCADA (Supervisory Control And Data Acquisition). Furthermore they will also build on CLC/TC-57 in providing amendments to the ENs on (Communication networks and systems for power utility automation - EN-61850), along with Application integration at electric utilities (prEN-61968),

energy management system application program interface (EMS-API) (prEN-61970) and on Power systems management and associated information exchange (EN-62351). The added value will also address the CEN-CENELEC-ETSI Coordination Group on Smart Energy Grids, CG-SEG (incl. the M/490 and its iteration) and EN-IEC-61850 (Distributed Energy Resources).

4. Concepts, architectures and use-cases of AI assisted smart PV

Solar energy has many important advantages, but also few important drawbacks. Among the advantages, it is a highly efficient energy source, which significantly advanced technologically in the recent years. It is a low cost and highly scalable, environmental friendly technology of energy generation. The main drawbacks of PV are cost/energy ratios (still improving and in 2020 historically becoming the cheapest energy source on Earth, however in highly solar irradiated geographic areas only), intermittence of power supply and not linearly fluctuating power output. Solutions for the areas of problems haunting PV are under significant development correspondingly with new materials and nano-engineering of the solar cells designs and fabrication methods, battery storage (or smart grid integration enabling input of PV generated surplus power to be consumed somewhere else) and electronic control equipment stabilizing electric output (smart hybrid converters and other devices). Furthermore facing the above problems many different optimization techniques were considered and implemented for PV modules and installations, mainly based on standard statistic techniques combined with numerical and analytical methods. Many of the these optimization techniques were also implemented by PV installations (or even PV modules) integrated electronic circuitry embedded in inverters, hybrid inverters, microinverters and alike. The better the optimization performance the higher the efficiency and power output stability of the optimized PV system which partially mitigates the main drawbacks of the PV technology, especially if it is interconnected to a smart power grid. Most of the PV optimization techniques considered were however classical and the recent development in Artificial Intelligence and Machine Learning can bring important added value in terms of better optimization of the PV modules and installations operations, hence further limiting the disadvantages of the electric solar energy.

The main areas in which AI can improve the PV performance are in solar cells designs and production phase, Planning of optimal solar cells systems deployments and optimization of solar cells operation in power systems. Solar cells designs and production phase comprises basic modeling of solar cells (materials, design and production technologies to devise new structures and designs, in terms of e.g. optimization of multijunction cells, that haven't been considered yet but might surpass the efficiency of the current top solar cell designs). Planning of optimal solar cells systems deployments is about forecasting and modeling of meteorological data for weather dependent insolation patterns, shading, etc. - e.g. AI assisted automated insolation analytics and interactive maps for smart PV deployments, optimal sizing of photovoltaic systems based upon AI assisted modeling. Optimization of solar cells operation in power systems concerns AI assisted optimization of electricity generation in solar modules within grid-connected PV systems (machine learning upgraded electronic circuitry for improved MPPT, fluctuations stabilization, etc.), AI for PV performance loss rate determination and power forecasting on a level of single solar cells, solar modules as well as whole installations, from private residential PV setups, up to large scale PV power plants, advanced automation and optimization of Operation and Maintenance (O&M) of PV installations (both small and large scale) and their smart on-grid integration, including AI assisted PV powerplants predictive management (using AI and machine learning to learn patterns in the electric fluctuations to be able to predict failures and support operations in terms of prevention in right time rather than mitigating failures that have already occurred), AI enabled concentrator PV (CPV) learned productivity under variable solar conditions, AI assisted optimization of smart distributed PV integration with power grids towards interconnected and digitalized energy market - towards energy production with consumers changed into prosumers by local power generation enabling PV, complemented with AI to optimize all integration processes. The examples for the latter point (smart PV integration with smart grids) involve many possible applications of AI, such as e.g. AI for increasing the smart grid awareness, machine learning methods to improve on the statistical based power grids net-load forecasting with enhanced behind-the-meter PV visibility (including various models, e.g. based on recurrent neural networks for ahead in time net-load prediction under high intermittent solar penetration in power grids), AI for demand response potentials with high penetration of behind-the-meter solar with storage, AI assisted PV integrated smart grid connectivity tracking in real-time with various machine learning methods for state and events tracking, AI algorithms for managing PV penetrated smart grids in a way to optimize intermittence of solar power with power storage control, AI assisted carbon intensity awareness in the grid power production for the smart PV operation integrated with intelligent energy efficiency control, AI assisted integration of smart meters data to increase renewable energy penetration in different parts of the power grid (data mining and machine learning on vast amounts of bidirectional smart electricity meters data to improve over time operation

parameters and physical restructuring of the power grid, towards a future of implementing automatically reconfigurable network topologies of electric power grids), AI assisted tokenization of virtual energy market (involvement of blockchain technology and smart contracts to securely tokenize prosumers generated surplus PV energy amounts, that physically enter the power grid but virtually enter a new generation of a distributed energy market with AI assisted algorithms for auctions of the energy selling/purchasing, so that the prosumers can gain on the transactions regarding their generated energy or possibly get it back from the grid for free in different locations and time), and others. Hence the approaches that can be used with applying AI to smart PV systems are vast and include among others: machine learning (with many variants including, supervised learning with classification and regression, as well as unsupervised learning with dimensionality reduction, clustering and association, deep learning and reinforced learning, quantum machine learning), neural networks (with many variants, including e.g. convolutional NNs, recurrent and feedforwarded NNs, generative adversarial NNs, quantum NNs), autonomous multi-agent systems (including particle swarm optimization), fuzzy logic (including quantum computational model based AI), expert systems (with knowledge bases and inference systems), evolutionary and genetic algorithms and other dynamically developed techniques and approaches. There is a wide consensus of advantages of new AI enabled methods over conventional statistical methods. An important aspect of the technical referencing of AI assisted smart PV (cf. Rządkowska, A., EITCI SESG AI assisted Smart PV Reference Standards, 2021) is not focusing on the theory of artificial intelligence and machine learning, but on practical AI applications in methods that are either ready to apply to PV operations or need only industrial level research and development.

5. Concepts, architectures and use-cases of AI assisted smart PV

Applying AI to important tasks for smart PV systems deployments and operations is undergoing significant investigation for several years already. The recent progress of AI may be very beneficial to support PV energy transition on a large scale. How exactly artificial intelligence can be successfully applied in different applications of photovoltaics? It should be noted that technical understanding of possible approaches is presently well developed however many particularities are under investigation in many currently ongoing R&D projects. Results of these projects will support further standardization of AI assisted smart PV.

5.1. AI assisted modeling of solar cell devices

This area of AI applications in PV has been discussed e.g. by Xu, 2019 or Miyake and Saeki, 2021.

In general a physical model governed by mathematical formulation accurately describing a solar cell design is a critical tool in for better understanding and fine-tuning of the characteristics, performance and optimization of a solar cell device. AI methods can in general assist in design and fabrication of solar cells.

A good example of how AI and machine learning supported modeling can benefit optimization of solar cells designs and construction is in the plasmonic enhancement of solar cells (cf. Jacak et al., 2011-2020). This can be well explained on a new generation of perovskite solar cells. An ordinary perovskite solar cell utilizes a perovskite structured compound (i.e. material with the same crystal structure as the CaTiO3 - calcium titanium oxide), most commonly a hybrid organic-inorganic lead or inorganic tin halide-based material. It represents an emerging class of thin-film photovoltaic cells. Perovskites are efficient at absorbing light and transporting charges which are the key material properties for producing electricity from the sunlight. In contrast to traditional p-n junction semiconductor solar cells (like Si cells), perovskite cells are soluble in many different types of solvents and remain semi-transparent after crystallization in very thin layers. As such, perovskite SCs may be easily ink-jet or screen printed in simple roll-to-roll processes or even sprayed onto large surfaces similarly like ordinary paints that when activated with chemically induced crystallization process create thinfilm layers (with the thickness below 1 µm) also relatively easily further integrated in elastic perovskite solar cell device. Those properties make the perovskite cells significantly cheaper in fabrication and very well suited to mass-output market uptake and vast applications (such as so called energy smart buildings elevations coverings of variety of geometries, semitransparent windows, roofs coverings, outdoor furniture, vehicles or even clothing external surfaces that may produce enough power from the sunlight to e.g. charge a personal mobile device). The main problem of the perovskite solar cells are lower efficiencies in applications-required chemically stable solar cell device configurations that might be greatly improved with optimized metalization in form of nano-particles inclusions and plasmonic energy mediation effects (cf. Jacak, 2020). This concept was proven specifically in perovskites in the initial experimental trials with a surprisingly strong magnitude of the plasmonic efficiency enhancement observed for perovskite (well beyond magnitudes in traditional p-n

junction solar cells) but is not yet understood in terms of physical mechanisms involved and not described in physical models, nor developed commercially. Here with the aid come advanced ML enabled methods for modeling towards optimization and fine-tuning of the possible to employ very strong plasmon photovoltaic enhancement in metalized perovskite solar cells. This requires development of a microscopic quantum mechanical model of the new channel of plasmon mediated enhancement of the PV effect in perovskites which was confirmed in the recent experiments, taking into account that perovskite SCs hold a strategic potential for the EU, which managed to secure in the recent years a very strong position in terms of global competition in this area. A strong increase of the perovskite SCs efficiencies (the experimental record is 40% relative increase due to metalization as achieved experimentally) is most probably due to the reduction of the exciton binding energy, but not of plasmon induced strengthening of photon absorption known from the p-n junction solar cells (like the metalized Si cells). On the technological side, nanoparticles would be embedded in the perovskite compounds close to the interface with the electron or hole absorber in the architecture of a hybrid chemical perovskite cell. Such cells operate in a different manner than conventional p-n junction cells, resulting in a different type of the plasmonic PV effect, which, however, is surprisingly strong. Application of adequate treatment in quantum models (e.g. the Fermi golden rule to the coupling of the dipole near-field-zone - lower distance than the wavelength - radiation of surface plasmons in nanoparticles to the band electrons in a nearby semiconductor) can lead to advancing designs with AI enabled parameter optimization in a technological finetuning towards the innovative product development. This requires processing huge amount of data to account for most proper adjusting of the identified contributing components of this effect, an optical one present in pn junction cells and resolving itself mainly to a photon absorption growth, and an electrical one - the newly discovered in perovskite cells apparently beyond absorption in a common general microscopic model. Model parameters optimizing for complex system is certainly a domain in which AI and ML can excel in current stage of these methods and technology development.

In general theoretical models describing solar cell device operation (in terms of physics of semiconductor structures involved) are primary tools in optimization of PV products efficiencies. A solar cell as a physical system is generally a simple semiconductor layered structure device of a p-n junction diode, producing electricity current from absorption of photons in a photovoltaic effect. Dominating semiconductor material in PV technology is the silicon - Si, either monocrystalline or polycrystalline. Depending on the complexity of the structure of the single-layered solar cell device (or a number of active solar cell layers in case of so-called multi-junction solar cell devices) the efficiencies to convert sunlight energy into electricity are between several percent up to even 40 percent (in complicated and expensive devices). Creating a numerical model of a solar cell involves most importantly its interaction with the e-m field. The e-m field simulation and its interaction with a semiconductor device can be done in specialized numerical methods such as the Finite Element Method (FEM) within a modeling suite called COMSOL. The modeling of the semiconductor device on its own is done in different approaches using electronic modeling tools used in electronic industry. The most important modeling parameters involve diode saturation current, series resistance, ideality factor, shunt resistance and the photocurrent (PV generated electricity). Many numerical as well as analytical approaches has been developed to simulate mutual interdependence of the solar cell characterizing parameters. Although the I-V relationship (referred to as I-V curve) is highly non-linear for solar cells which caused problems for many algorithms. Furthermore computational complexity for more complex devices is also problematic for a standard numerical approach. The more advanced approach partially based on ML and AI have been recently investigated with optimizing and modeling of the PV devices with a high rate of success. The currently identified as most promising directions were in simulated annealing combined with artificial neural networks. E.g. Karatape et al. developed an AI solar cell design optimization model basing on the Sandia National Laboratory data for PV performance in a function of operating temperatures and solar irradiation. A simple analysis proves that the relationship between the I-V curves is nonlinear and cannot be easily expressed analytically, which makes a great problem space for AI neural network to be utilized. Their 2006 paper proposed neural network based approach for improving the accuracy of the electrical equivalent circuit of a photovoltaic module, and as the equivalent circuit parameters of a PV module mainly depend on solar irradiation and temperature, the dependence on environmental factors of the circuit parameters was investigated by using a set of current-voltage curves. In a proposed model certain data points are chosen from the corresponding I-V curves (the selection of points is done upon a most optimal simplified but still accurate on the required level representation of the curve by a minimal number of points). The artificial neural network

model is trained with as many possible combination of operating parameters (irradiation and temperature operation - the neural network is trained with empirical I-V curves, and the equivalent circuit parameters are estimated by irradiation and temperature readouts only, without nonlinear equations solving that would be necessary in conventional methods). The operation of this one of the first solar cells AI models has been verified in an experiment with the achieved empirical data highly corresponding with the data attained from the NN model and what's by far surpassing the accuracy from conventional numerical approaches. The results of ANN training was the a possibility to model an abstract device in given parameters combination (irradiation in temperature) to generate in ML approach an I-V curve enabling for the data to be input to a diode solar cell model. Different approach is in generating I-V empirically and determining operating points using ML (based on operating parameters of an experimental solar cell, I-V tracer and a weather station for readouts of irradiation level and the temperature and comparing the readouts with data attained in a model to provide a learning enabling feedback. The parameters generated by the model, despite being subject to errors and impossibility to discriminate between the effects on the operation of a modeled solar cell device of temperature vs. irradiation, were still superior (about 3 times more precise) then the ones possibly obtained from conventional models (in terms of Townsend equations solutions). Yet another approach is with utilization of the simulated annealing, as proposed by El-Naggar et al. (comparable with the genetic algorithms and particle swarm optimization methods). The operation of simulated annealing is based on defining an objective function and its minimization then validated against the experimental data (the method resulted with a Root Mean Square Error RMSE of just 0.0017 for a single diode solar cell model, which is considered highly accurate). On the other hand Askarzadeh et al. has proven that the Harmony Search optimization process provides even better precision, with the AI optimization method aiming at imitating an improvisation in music to find a harmony. Accordingly with the proposal an objective function based on the single diode model was minimized with respect to a particular range and the Harmony Search method was able to extract the main solar cell device parameters with an error (RMSE) significantly smaller (below one-tenth) than obtained in the simulated annealing method.

5.2. AI assisted smart PV applications in weather forecasting and automated insolation analytics for interactive irradiation mapping for smart PV deployments

This scope of AI application for PV is well addressed by e.g. Choi et al. (2019). When the solar cells device is manufactured and integrated into a solar module its efficiency is well defined. Upon its deployment it can be influenced with electronic control (involving smart hybrid inverters or a single panel adequate microinverters involving e.g. methods of AI assisted MPPT). However before the operational AI optimization of a PV installation is possible, an important aspect for proper planning in deployment of PV is weather forecasting (which also has an important role for smart grids operations). Predicting weather is not an easy task due to the complexity of the system, but making some well-informed analysis enables with the use of advanced ML models of some reasonable short term ahead of time estimation. Furthermore quantifying average irradiation and temperature (as the main important, however also backed up by humidity, wind speeds influencing cloud coverage changing affecting irradiation, daily sunshine duration and sunlight incoming angles, etc.) conditions allows to estimate the parameters of the PV installation that would generated certain required power to cover the expected loads. Meteorological analysis and estimation of the key weather parameters is hence an important factor in deciding the power output of the PV installation, as these parameters have an overwhelming influence on the efficiency of solar cells operation. Dedicated instrumentation (pyranometer, pyrheliometer, two-axis solar trackers, etc. are used to directly measure global and direct solar radiation). In certain places this data is available from already performed measurements stored in accessible databases (e.g. a database of NREL). Usually however these parameters are rather difficult to be obtained for given sites because of the PV systems installation planned in areas were these parameters have not been measured (low availability of data) and the direct measurements impractical because of the high cost of the equipment. Hence AI is an important alternative which recently has been used in aiding of solar irradiation mapping (along with other PV important meteorological parameters). How AI methods can be used to support mapping solar irradiation? Among multiple national and international projects there is gathered huge publicly accessible geographic data on insolation. An important application of AI assisted PV is employing data engineering of databases of insolation to provide a scalable and fast solution for computational analysis of conditioning PV parameters insolation in any geographical area (with using machine learning and AI estimation techniques for the low-data regions). An industrial case is the Project Sunroof initiated by Google as a planned extension to Google Maps product,

that would provide full analytics of insolation data from multiple sources joined and processed by Google algorithmics and merged with Google Maps. Project Sunroof was started by a Google engineer Carl Elkin. The initiative's purpose is mapping the planet's solar potential, one roof at a time. The Project Sunroof primarily works to encourage the private adoption of solar energy by providing a set of tools to facilitate the purchase and installation of solar panels. Using data from Google Maps to calculate shadows from nearby structures and trees and taking into account historical weather and temperature patterns data, the Project Sunroof calculates how much money a user can expect to save yearly by making use of the solar power PV installation. In addition, the Project Sunroof also provides a list of local solar power retailers capable of installing solar panels in that area. The Project Sunroof was initially launching only in the United States, for the cities of Boston, San Francisco, and Fresno. The project has then expanded to cover larger metropolitan areas across the United States and is currently developing globally. The Google's Project Sunroof bases on the data of imagery and 3D modeling and shade calculations from Google, weather data from the National Renewable Energy Laboratory (NREL), utility electricity rates information from Clean Power Research, solar pricing data from NREL's Open PV Project, California Solar Initiative, and NY-Sun Open NY PV data, solar incentives data from relevant policy actors, Solar Renewable Energy Credit (SREC) data from Bloomberg New Energy Finance, SRECTrade, and relevant state authorities, aggregated and anonymized solar cost data from Aurora Solar software. A similar but less visual solution - PVWatts tool - was developed by the National Renewable Energy Laboratory (NREL). Similarly as Project Sunroof It estimates solar energy production in taking into account multiple factors, e.g. sun shading by objects, typical weather patterns, equipment parameters, etc. The estimations are based on multiple databases, in many cases with many historic data for proper predictions e.g. of averaged weather conditions for insolation, as well as complicated analyses for shading (algorithms take into account even recent growth or removal of trees to most accurately analyze solar power potential, hence proper datamining in AI/ML techniques is important enabler of this technology for its future development). Project Sunroof's expanded its reach to Europe partnering with E.ON and released a new online tool in Germany based on Google's Earth mapping to help residential customers determine whether their roof is wellsuited for solar panels and how much money they could save by installing solar. The main focus of this area of AI assisted smart PV is to help raising consumer solar awareness, and on making the path to solar easier for its customers and operations. Project Sunroof's estimates in Europe include weather data from Meteonorm, a product by Meteotest, a Swiss company specializing in solar irradiance data. AI enabled extensions involve recent cooperation between Google and Total (French energy company with a large network of gas stations in Europe and in Africa). Total developed the Solar Mapper tool using AI enhanced Google solution to make solar potential estimation faster and easier, driving the adoption of solar power globally by using machine learning to model estimates in low-data areas. For an example of France the project increased the territory covered for solar estimation from 30% to 90% using AI, which in turns encourages solar power uptake. Estimating potential output of solar panels on private houses, or on commercial and industrial sites is an important incentive in encouraging the PV uptake worldwide. The actual AI algorithms used generative predictive models to enhance the 3D data used to model shade and calculate solar potential where high-quality satellite images are not available. By doing this, AI helps to estimate the solar output for positioning solar panels on any location. Principal investigator in the project is Philippe Cordier (and the team involves Google Earth Engine and Google Cloud machine learning experts). Also widespread adoption of rooftop photovoltaic systems in residential PV installations, as well as growing grid-scale solar systems requires a significant change in how system operators, utilities and solar system providers map system adoption, track it is impact, and plan new deployments. Currently available information suffers from disparities in resolutions (satellite imaging is usually detailed in dense populated areas but much less so in rural areas, also significantly differentiated in terms of countries). It also often lacks crucial details about time and location. The availability of such information would change how the system is planned and managed. Artificial intelligence and machine learning techniques may prove to be crucial to effectively map of the optimal deployment of PV systems by supporting lower intensity data with estimation, thus supporting highly aware and hence optimized distribution networks with high accuracy and detail. The AI assisted in generation and continuously updated global database joining public accessible data from project such as NREL insolation database or Google's Sunroof Project may be a future of aware planning of small-to-large scale solar energy deployments. Recent advances in AI in effective processing huge datasets enabling to combine information available at a large scale (such as satellite imagery, Google street view images processed with AI vision for unlocking machine-understanding of shading and high-resolution irradiance data from weather stations and historical measures of solar irradiation

parameters, hold a potential to generate a vastly optimized plans for location and size of future solar deployments globally thus supporting certain reconfigurations and reconstructions of the transmission lines or distribution grids as necessary for future deployments. This area of application holds potential especially if combined with high spatiotemporal granularity, which requires adjusting of most proper methods in machine learning approaches to process all the extremely detailed data and address a variety of applications such as identifying bottlenecks, estimating the hosting capacity of distribution systems, planning electric storage capacity in dependence to conditioning circumstances of locations, improving wholesale price predictions, and creating more accurate models of consumer adoption.

5.3. AI assisted carbon intensity awareness in the grid power production for smart PV operation

This field of AI application for smart PV has been discussed by Khana (2018) and Tuzun (2020). Prosumer centric, distributed energy model enabled by smart PV in standard integration with the smart grid, enables PV power generated surplus to be fed into the grid. The bidirectional smart meter measures the power input to the grid and enables intake for consumption when the electric energy is needed beyond the current capacity of the PV generation. In this model however the smart PV and energy consuming appliances integrated installation does not know when it is most optimal to actually use the energy generated In surplus that would be fed to the grid. This requires awareness not only on electric net loads in the grid but also awareness of when the grid power has the smallest CO_2 footprint. The resolution of the carbon intensity forecast is required to be at least on a regional level for the technology to allow prosumer installations to actually condition their energy consumption on this environmental factor. For the technology to work AI and Machine Learning is a key enabler, because of a sophisticated power system modelling required to accurately to forecast the carbon intensity and generation mix up to 4 days ahead for individual regions. Such achievement had been already introduced in Great Britain in terms of the Carbon Intensity API project (of the UK National Grid ESO). The outcomes of the project are successful to the extent that the UK National Grid has produced and delivered thousands of WiFi connected bulbs that change the emitted light color to green whenever the electricity in the grid is dominantly from low-carbon sources (thus giving a signal that it is a good and environmentally clean time to do a laundry in a washing machine, to turn on a dish washer or to start charging an electric car – in smart home integrated IoT, all this would be automatic along with properly managing surplus of power generated by AI assisted and interconnected PV installation accordingly with the awareness of the current regarding the carbon intensity of grid power). The open API of the project enables prosumers and smart devices to schedule energy consumption in coupling with smart PV local power generation in order to minimize CO emissions at a regional level. The data in the API estimate and indicative trend of regional carbon intensity of the electricity system in 96 hours ahead of real-time, thus providing programmatic and timely access to both forecast and estimated carbon intensity data (limited to electricity generation only). The CO₂ emissions (within a measure of how much of CO_2 is produced per kilowatt hour of electricity consumed) are gathered from all large metered power stations, interconnector imports, transmission and distribution losses, and account for national electricity demand, embedded wind and solar generation. The API allow developers to produce applications that enable consumers or smart devices to optimize their behavior in such a way as to minimize CO_2 emissions. While the actual value is the estimated carbon intensity from metered generation, the more ambitions target is the time-ahead forecast value. Since the carbon intensity of electricity is sensitive to small changes in carbon-intensive generation. Carbon intensity varies by hour, day, and season due to changes in electricity demand, low carbon generation (wind, solar, hydro, nuclear, biomass) and conventional generation. National Grid ESO forecasts the carbon intensity and generation mix of electricity consumed across 14 geographical regions in Great Britain. The spatial and temporal characteristics of carbon intensity can be visualized on maps or be transferred in computational datasets. How the AI and Machine Learning techniques are actually involved in this application? The demand and generation by fuel type (gas, coal, wind, nuclear, solar etc.) for each region is forecast several days ahead at 30-min temporal resolution using an ensemble of state-of-the-art supervised Machine Learning (ML) regression models. An advanced model ensembling technique is used to blend the ML models to generate a new optimized meta-model. The forecasts are updated every 30 mins using a nowcasting technique to adjust the forecasts a short period ahead. To estimate the carbon intensity of electricity consumed in each region, a reduced GB network model is used to calculate the power flows across the network. This considers the active and reactive power flows, system losses, and the impedance characteristics of the network. The carbon intensity of both active power flows (gCO /kWh) and reactive power flows (gCO /kVArh) is then calculated and the CO flows are attributed around the network for each 30 min

period over the next several days. The carbon intensity of the power consumed in each region is then determined. The same approach is used to estimate the proportion of each fuel type consumed in each region. A more detailed description of the Carbon Intensity API methodology can be found in reports by Rogers, A., Bruce, A., et al., 2021.

5.4. AI assisted integration of smart meters data to increase renewable energy penetration

One of the important applications of AI for smart PV is the use of machine learning techniques to process (including joining, synchronizing, standardizing and interpolating) electric data from numerous sources (especially smart meters) in order to more accurately estimate the state of the electric grid. This will ultimately support efficiency for interconnection and/or operation of more PV systems and other Distributed Energy Resources (DER) in power grid while simultaneously enhancing reliability, stability and resiliency of power provision. This area of AI application involves measurements and sensor data synchronization, data mining for error detection and identification, data based reasoning and machine learning based optimization. Vast amounts of the smart meters data provided by the Advanced Metering Infrastructure (AMI) and Phasor Measurement Units (PMU) is a great target for AI assisted processing, reasoning and optimization methods that will lead to significant increase of smart PV installations grid-integration efficiency and scale. The scope discussed has been addressed by e.g. Boza et al. (2021), as well as Bañales et al. (2021).

5.5. AI assisted PV powerplants predictive Operation and Maintenance (O&M) optimization

AI and ML methods are well suited optimize O&M of photovoltaic (PV) power plants by detecting, classifying and monitoring anomalies and malfunctions along with the prediction and mitigation. The AI systems can predict failures and prevent their occurrence based on vast data processing abilities with well-informed reasoning on the reasons and circumstances preceding possible malfunctions. Such predictive AI O&M solutions is of critical importance for industry-level PV power plants with large number of solar cells modules and complex interconnection systems, as due to the machine learning capabilities the system would increasingly better predict failures and allow to schedule proper maintenance. Predictive O&M is an important aspect of the smart O&M to sustain a high profile and economically optimized performance of a solar PV plant and reduce its downtime. Real-time monitoring data of various system outputs, such as the as power output, other more detailed probing of the electricity signature, detection of fluctuation patterns, temperature sensors readouts, combined with accurate weather information sensor networks can be meaningfully processed by AI algorithms in neural networks models trained and self-improving in identification of the common fault class patterns. The most adequate systems are various models of neural networks as well as hierarchical generative models and as proposed in recent projects – probabilistic information fusion framework fed with data from both the sensor level and the system level. More details can be found e.g. in a paper by Chang et al. (2019).

5.6. AI for increasing the smart grid awareness

This area of AI application were discussed e.g. by Omitaomu and Niu (2021), as well as by Jiao (2020). AI and ML can be used to provide grid operators smart monitoring and decisions support in real-time analysis and visualization of the electric power system operations. AI assisted cloud computing enables advanced monitoring, while real-time analytics provide a model for leveraging multiple data sources to correlate, verify, and interpret system telemetry in environments with high scale and low data fidelity. Machine learning is especially well applied in such areas as fluctuations in data can be detected with increasing accuracy of prediction with increasing history of operations and available data. Experience from systems design in related fields shows that in sufficiently complex systems, no single data source can be entirely accurate or trustworthy, but an approach that leverages multiple sources and applies intelligent data interpretation can provide an extremely reliable, high-fidelity systems view. This area of application of AI for smart monitoring along with capabilities in integrated power system simulation and data analytics with machine learning or deep learning enables provision of advanced, integrated situational awareness for the distribution grid and contributions to area-wide flexibility.

5.7. AI for PV performance loss rate determination and power forecasting

This area of applying AI is by using spatiotemporal Graph Neural Network models in a so-called Reliable System-Topology-Aware Learning Framework. More details in this regard has been presented by the US Department of Energy Project: Robust PV Performance Loss Rate Prediction: Using Spatiotemporal Graph Neural Network Models in a Reliable System-Topology-Aware Learning Framework (DE-EE0009353, 2021).

A similar discussion can be also found in a paper by Zhou et al. (2021). The AI and ML techniques are used to analyze data from a large number of neighboring PV systems in order to extract high amounts of information about their short- and long-term performance. Machine learning methods are planned to be used to overcome data quality issues affecting individual plants. Development of spatiotemporal Graph Neural Network models addresses critical questions of long- and short-term performance for fleets of PV plants for their operators and also for the grid status determination. The proposed learning techniques advance both analytical techniques for long-term performance of PV power plants and deep learning techniques, and can mitigate the negative impact of PV plant or sensor failure or unreliable input data.

5.8. Deep Learning probabilistic net load forecasting with enhanced behind-the-meter PV visibility

Another area of AI application for PV (as introduced by Kirschen et al. in 2018 and developed further by Cha and Joo in 2021) is using machine learning and deep learning techniques to predict the electric load one day in advance in areas that have large amounts of behind-the-meter solar. The AI predicted information on the future net load will allow operators (or AI supported control systems) to manage the electric grid more efficiently (in terms of compensating loads and costs). The deep learning based probabilistic forecasting framework for a day ahead net load at substations aims at separation of the behind-the-meter photovoltaic generation from net load measurements and quantifies its impact on net load patterns. Actual AI DL applications requires implementation of the transfer learning models that would enable transferring the knowledge learned from geographic locations with rich sensor data to diverse locations where only the substation measurements are available. The framework could be validated using measurement data from public grid databases as well as basing on the Solar Forecast Arbiter platform.

5.9. AI for demand response potentials with behind-the-meter solar with storage high penetration

This aspect of AI application assisting smart PV (discussed in detail by Wattam et al. in 2020, as well as by Esnaola-Gonzalez et al., and Prabadevi et al. in 2021) is based on machine learning techniques to predict the electric load in areas with large amounts of solar energy to enable more efficient grid operation. ML application will also be able to forecast the capacity available to the grid from electric loads that can be turned on or off depending on the balance between electric demand and generation. Recent advances in AI modelling can enhance the accuracy of net load forecasting, the observability of net load variability, and the understanding of the coupling between net load and demand response potentials. There are two models under development for addressing hybrid probabilistic forecasting which can provide better spatiotemporal information.

5.10. AI assisted PV integrated smart grid connectivity tracking in real-time with heterogeneous data sources by application of graph learning assisted state and event tracking

Another scope of AI application in smart grid integrated PV is for its connectivity tracking in real-time with heterogeneous data sources by application of graph learning assisted state and event tracking. This area has been recently researched by i.a. Albayati et al. (2021), Koshy et al. (2021), as well as Esenogho et al. (2022). Machine learning techniques enable integration of large-scale electric data and use it to calculate the overall state of the electric network. This scope partially expands on the Operations & Maintenance (O&M) AI smartPV application but addresses it from a specific perspective of graph based learning which might be especially adequate to a grid graph-like topology. The resulting AI enabled tool will detect connectivity changes and faults in the grid and update the grid models accordingly, which will improve the situational awareness of power grids with large amounts of solar energy by exploiting a large volume of data and measurements available from a highly diverse set of sources (especially in terms of measured characteristics of the electricity in the grid). This scope of AI application for smart PV also considers tools to detect, identify and track network topology changes, that might be due to unexpected disturbances or switching events by exploiting the recently developed sparse estimation methods in the data analytics area.

5.11. Variational recurrent neural network based net-load prediction under high solar penetration

A different in applications is using artificial intelligence and machine learning techniques to create tools that can predict future electric loads (e.g. in scale of hours or days) in areas with large amounts of behind-the-meter PV systems and deliver savings in the operation of the electric network. There are proposed concepts (e.g. Liu et al., 2019) in development and validating of variational recurrent model-based algorithm for time-series forecasting of net-load under high solar penetration scenarios. In uncertainty of cloud covering weather conditions, varying solar irradiance, geographical information with details including shading, and the measured
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end-use load may theoretically guarantee tight bounds on the net-load prediction, that can be obtained from vast datamining and properly trained machine learning models working on that data jointly.

5.12. AI enabled concentrator PV (CPV) learned productivity under variable solar conditions

Beyond standard PV installations, artificial intelligence and machine learning techniques can be used also to model and optimize concentrator PV plants operations in order to assist human operators in their decisions, especially during variable cloudiness conditions. The machine learning techniques can be applied to extensive, high-resolution, inferred DNI data, cloud profile and vector data, and related solar field thermal collection data in order to develop prescriptive models to optimize solar field collection under variable conditions while minimizing long-term PV receiver damages and other negative effects. Validation of methods that can be used to this end for CPV are currently underway in regard to operating concentrating solar power (thermal) CSP facilities and start to publish methodological details for broader investigations. Even though that there are certain differences in concentrating solar power for thermal and PV applications (the former being usually central while, the latter much more distributed into multiple lower-power PV receivers), certain disadvantages of the CSP vs CPV (including environmental issues), seem to favor the latter at least in a long term of the technology development, and AI assistive role in optimization of CPV operations is certainly an important aspect. More details in this regard can be found in papers by Renno et al. (2020) and Tina et al. (2021).

AI advances to improve and further optimize the performance and reliability of individual solar cells, solar modules and PV small-to-large scale installations (from residential to utility power plants), along with AI enabled predictions of solar energy output and electric-network situational awareness (also including the awareness of how clean the energy in the grid is in the current moment along with ML prediction for ahead of time, to enable smarted AI assisted energy consumption management for reducing emissions) play an important role in supporting large scale PV energy transition. The current cooperation which is beginning to scale internationally between AI experts and solar energy industry stakeholders will be further stimulated by the relevant technical standardization efforts, with a goal to advance AI smart assisted PV technology. The standardization activity in the scope of AI assisted smart PV will facilitate its faster market uptake and speed up the clean energy transition globally.

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G-09. Energy Economics, Markets and Policy

In-Depth Assessment and Feasibility Study of a Solar PV Farm for a High-Altitude Region: Bridging the Gap Between Technical Potential and Market Barriers in Kyrgyzstan

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Abstract

Kyrgyzstan is known for being a high-altitude and cold climatic country of Central Asia. Due to mountainous characteristics and permanent glaciers, enormous water resources are abstracted at the county's disposal. Because of the endowed water resources, the majority of the power is generated with hydropower facilities. However, the Kyrgyz power sector is facing energy insecurity because of the hydropower facilities. Despite social, environmental, and ecological and energy issues, the local government focused on building new hydropower plants. On the other hand, Kyrgyzstan is blessed with a great potential for solar energy because of its geographical characteristics which can ensure a sustainable power supply. To bring sustainability to the Kyrgyz power sector with the help of renewable energy, the presented work utilizes the untapped solar PV potential of Kyrgyzstan to perform a feasibility study with detailed techno-economic analysis by considering the latest energy legislation framework. The study shows that the solar PV farm is a suitable technology for sustainable electricity supply in Kyrgyzstan over hydropower plants. The study further identifies the solution to bridge the gap between the technical potential of solar PV and market barriers.

Keywords: high-altitude, grid integration, solar PV farm, sustainable energy, economics, markets & policy, feasibility study, Kyrgyzstan

1. Introduction

Kyrgyzstan is a high-altitude mountainous country situated in Central Asia. The Tien Shan mountain range covers more than 90 % of the Kyrgyz territory which results in a large number of glaciers and permanent snow. Therefore, Kyrgyzstan is blessed with abundant hydro resources. The plentiful water resources are responsible for the production of more than 90 % of the electricity with hydropower plants, which makes the Kyrgyz power sector highly dependent on hydro resources for meeting its conventional energy needs (Kalybekovich and Djumabekovich, 2012; Mehta et al., 2021).

However, the Kyrgyz power sector experiences a major challenge because of the growing and fluctuated interseasonal energy demand. Hydropower plants (HPP) in the Kyrgyz Republic generate the highest share of electricity during summer. Within this season, the installed hydro capacity is sufficient to address the demand as the water flow in rivers is sufficiently high. Because of the high-altitude and mountainous characteristics, Kyrgyzstan experiences a cold climatic zone with extended winter (-25 to -30 °C in the mountainous areas). As a result of the extreme winter conditions, the flow of water decreases in the rivers leading to reduced power production not being able to cover the electricity demand. Due to the long and harsh winters, the sizable amount of urban population resort to electric operated house heating systems which leads to high electricity consumption in winter. During this season, Kyrgyzstan is strongly dependent on the import of electricity from neighboring countries (Balabanyan et al., 2015; Mehta et al., 2021).

Access to electricity is currently covering the whole territory of Kyrgyzstan. However, the Kyrgyz power sector is not capable to meet the high demand in winters because of the high reliance on hydropower generation, and therefore, the Kyrgyz population experience persistent power shortages / outages (National Statistical Committee of the Kyrgyz Republic, 2017). According to the results of the quality of energy delivering services survey in Kyrgyzstan made by the NSC in 2015, only 11.8 % of households had uninterrupted power supply, while 64.4 % had power cut several times a year and 0.5 % had daily power cuts (National Statistical Committee of the Kyrgyz Republic, 2017). Electric power transmission and distribution losses were nearly 24 % of the total power output in 2017. Furthermore, most of the operating hydropower plants were built more than 30 years ago (Balabanyan et al., 2015). As Kyrgyzstan falls

under active seismic zones, the old-age hydropower plants are most vulnerable to damage due to frequent earthquakes. A relevant study stated that the destruction of any dam as a result of a natural disaster (earthquake or landslide) could bring harmful consequences, including human life losses. In the case of the destruction of a large dam in Kyrgyzstan, large floods waves could go downstream generating huge devastation in the neighboring downstream countries (Havenith et al., 2017; Mussa, 2018).

Agriculture is a very important source of income that would be threatened by HPPs. Central Asian countries are important agricultural producers. Given the fact that they receive rare water from rainfall, they rely mostly on irrigation from the upstream countries. The countries of Central Asia have a total irrigated area of 100,000 km², requiring vast quantities of water. Moreover, irrigation uses considerable amounts of water, and that makes agriculture the biggest water user sector in Central Asia (Havenith et al., 2017). The construction of new HPPs might represent a risk for Kyrgyzstan and it could make the water stress situation of the Central Asia downstream countries worse. Furthermore, the reservoirs of new HPPs take several years to refill, during that time, the downstream water would be reduced (Russell, 2018).

Moreover, hydropower projects can have several negative impacts on the environment. Hydropower dams impede the natural flow of rivers, and therefore, create migration barriers. Migratory animals require different environments for different phases of their life cycle. This effect may lead to the loss of biodiversity and ecosystems which are essential for humans (Mussa, 2018). Other negative effects of HPP include: '*Decreasing of groundwater, changing of water quality, drying of natural lakes, influence on the physical and biological environment, landscape destruction, deforestation and microclimate changes, among others*' (Tsvetkov, 2018).

Nevertheless, the government of Kyrgyzstan still focuses on developing and constructing new hydropower plants to improve the conditions of the power sector (IHA, 2018; Dikambaev, 2019). Naturally, the new hydropower plants will not be the most suitable solution due to the local boundary conditions. On the other hand, Kyrgyzstan presents an enormous solar energy potential due to its high-altitude characteristics. It has been estimated that the potential of solar energy in Kyrgyzstan is 60 % higher than in Frankfurt. Fig. 1 portrays the potential of solar energy in Kyrgyzstan. However, the great solar potential of Kyrgyzstan has not been exploited until now.





Fig. 1: The Global Horizontal Irradiation map of Kyrgyzstan (left) and comparison of solar irradiation between Naryn and Frankfurt (right), based on Solargis (2017)

2. Research objective and methodology

The current problems of the Kyrgyz power sector, as well as the untapped solar energy, have attracted more attention in the field of solar energy to supply sustainable electricity in Kyrgyzstan. Certainly, the utilization of unexploited solar energy to produce electricity through solar PV technology can suitably contribute to making the Kyrgyz power sector stable. However, there are very limited studies available that consider the in-depth assessment of a solar PV farm in Kyrgyzstan to identify its technical and economic viability under the special characteristics of the country. Therefore, the presented research focuses on developing a feasibility study to evaluate the technical and economic performance of a large-scale solar PV farm (100 MWp) in Kyrgyzstan, by considering particular conditions such as low-electricity tariff, minimal feed-in-tariff, cold climate, and high-altitude. Fig. 2 represents the methodology for the feasibility study divided into three main categories.

Firstly, a systematic diagnosis was carried out to assess the Kyrgyz power sector background and its challenges, as well as the technical potential of the available solar PV energy. Furthermore, the current Feed-in tariff (FIT) and market barriers in the country were identified and analyzed. Based on the systematic review, the feasibility study was performed, starting with the various site selection and the PV module. Moreover, the simulation model of a

large-scale solar PV farm (100 MWp) was developed with the *Polysun* software (Vela Solaris AG, 2021). A detailed techno-economic analysis was done to evaluate the viability of the proposed solar PV farm in Kyrgyzstan.



Fig. 2: Methodology of the feasibility study for a large-scale PV farm in Kyrgyzstan

3. Solar PV Farm Modelling

This chapter presents the modelling of a 100 MWp solar PV farm. The size was defined in order to identify the feasibility of the solar PV farm, as well as to evaluate the (simulation-based) performance of solar PV technology on a large scale for grid integration. In order to check the feasibility of a large-scale solar PV farm in Kyrgyzstan, the simulation study was performed by changing the locations through Kyrgyzstan that inevitably included the change in climatic condition as well as elevation.

3.1. Site selection

To observe the performance of the large-scale solar throughout the country, seven locations were selected from the seven regions of Kyrgyzstan. The climate and altitude vary across Kyrgyzstan and therefore such selection allowed to evaluate the performance of solar PV farm in various conditions. In addition to this, such a selection strategy was the first attempt in the context of Kyrgyzstan. Hence, the simulation results present a piece of novel information for local stockholders, private investors and policymakers. The selected locations are displayed on the regional map of Kyrgyzstan in Fig.3.



Fig. 3: Locations (site selection) for simulation of the large-scale solar PV farm

3.2. PV Module Selection

To select a PV module, a module selection analysis was carried out to identify suitable and available solar PV modules. There are several modules that were evaluated which are mostly available from neighboring countries (i.e., China and India). At the same time, the literature review identified that a Kyrgyz-German company called *New-Tek* manufactures PV modules. Hence, in order to reduce the import taxes as well as to assess the performance of locally

manufactured PV modules, the presented research selected a PV module of New-Tek from Kyrgyzstan for further simulations. The selected module specifications are listed in Tab 1.

PV module	Efficiency	Module area	Peak module	Short circuit
type	[%]	[m²]	capacity [W]	current [A]
Mono-Crystalline	18.3	1.67	300	9.75

Tab. 1: Specifications of selected photovoltaic module [based on (New-Tek, 2020)]

3.3. Simulation results

In order to get the most accurate results of the power output, a simulation of the 100 MWp solar PV plant has been developed. The solar PV system has been modeled with *Polysun* 11.3 simulation Software. After choosing the respective template (50a. Photovoltaics), the adjustment of specific parameters is required. The required technical specifications such as tilt angle, azimuth angle, declination angle, hour angle, zenith angle etc. were calculated based on Tiwari et al. (2016). One can review the mentioned literature for the equations and detailed calculation method. To design a 100 MWp solar PV farm the number of modules was calculated based on eq.1.

$$N_{modules} = \frac{P_{nom-plant}}{P_{nom-module}}$$
(eq.1)

$$P_{nom-plant}: Power of the PV plant=100,000 KWp P_{nom-module}: Module nominal power = 0.300 KWp$$

In order to optimize the arrangement of the inverters (ABB Ltd. PVS800-0500kW-A), the number of modules was

calculated as 334,400 (suggested by *Polysun*). To install large-scale PV farm, it is also necessary to calculate the required land area. The required PV farm area (to avoid shading) was calculated with eq. 2. The required area for a 100 MW solar farm is 58.19 ha (based on eq. 2).

$$\begin{split} A_{PV_{farm}} &= (N_{modules} \cdot A_{module}) + [(Raw spacing factor \cdot Height of module) \cdot (N_modules \\ & \cdot A_module)] \end{split} \tag{eq.2}$$

$$A_{module}: Area of the PV module = 1.67 m^2 \qquad N_{modules} = 334,400$$

$$Height of module = 0.035 m \qquad Raw spacing factor = 1.2$$

As stated by Baybagyshov and Degembaeva (2019), Kyrgyzstan's altitude varies from 800 to more than 4,000 meters above sea level. The difference in altitude of individual regions locations causes unequal availability of solar irradiation. The intensity of solar radiation is determined by climatic conditions, geographical location of the terrain, slopes exposure, and also the time of the year and the day. Direct solar radiation predominates in the highland region during the year. The peak of sunshine hours is reached between May and August, with about 130-155 hours of sunshine per month. Hence, the variable topography and climatic conditions of the country offer the variable PV power output for all selected seven regions. The simulation results are summarized in Tab 2. Also, Fig. 4 represents the detailed monthly technical performance indicators for all seven locations.

Tab. 2: Summarized simulation results for selected locations (Green = Highest, Orange = Medium, Red = Low)

Location	Annual global horizontal irradiation [kWh / m²]	Altitude [m]	Annual solar energy [GWh]
Bishkek	1,537	800	~ 152
Jalal-Abad	1,623	766	~ 154
Karakol	1,644	1,745	~ 163
Naryn	1,727	2,044	~ 174
Osh	1,607	963	~ 150
Batken	1,633	1,042	~ 154
Talas	1,699	1,244	~ 168



Fig. 4: Design performance indicators of 100 MWp solar PV farm at different locations in Kyrgyzstan [Monthly Global Horizontal Irradiation (GHI), Monthly solar energy production and monthly average temperature]

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It can be seen from Tab 2 and Fig 4 that especially high-altitude regions have a high potential to produce more energy as compared to low-altitude regions. For example, the energy output of Naryn is 174 GWh/a, while the power plant in Bishkek can produce 152 GWh/a. Because of the geographical locations, high-altitude regions are blessed with a higher amount of solar irradiation. Concerning Chitturi et al. (2018), high altitude regions are endowed with a great solar energy potential, opposed to what is commonly thought. Even though high-altitude areas are usually characterized by cold temperatures and long winters, the highest solar irradiation areas usually match the highest altitude regions, like mountain ranges. Therefore, the greatest solar power generation is presented in cold geographical locations because the efficiency of PV panels rises with low temperatures. Hence, the high-altitude and cold climacteric regions of Kyrgyzstan (i.e. Naryn) are the most suitable locations to harness more energy from the sun for large-scale solar PV farms.

The presented simulation study demonstrated the prodigious technical potential of solar PV in Kyrgyzstan. However, economic viability is a key indicator that influences the real execution of the project. Furthermore, the feasibility analysis developed in research has the aim to avoid the construction of new HPPs. Accordingly, the next sub-chapter compares and outlines the economic performance of a solar PV farm and a hydropower plant of the same capacity in the context of Kyrgyzstan.

3.4 Comparative economic assessment

There are fewer pieces of evidence / measures available to quantify the cost structure of the solar PV farm and hydropower plant in connection to Kyrgyzstan. Even though, to provide a rough idea about the cost compression, a generalized cost estimation was calculated for solar PV farm and Hydropower plant of 100 MW. The initial investment costs of the solar PV farm were calculated as the sum of the following element cost: Equipment cost (PV modules and the inverter), the auxiliary, the mounting structure, the soft cost (installation, site preparation). It can be highlighted here that the land cost in Kyrgyzstan is significantly inexpensive as compared to European countries. Fabinyi et al. (2020) mentioned that 1 ha (10,000 square meters) of agricultural land cost about 1,500 \in . The initial investment costs of the hydropower plant are calculated as the sum of the civil costs, the mechanical equipment costs, the planning costs, and the grid connection cost; times the size of the HPP. Fig. 5 shows the different costs taken into account for the calculation of the total initial cost of the PV Farm and the HPP. The values are calculated based on the sources Akker (2017), ENf (2020), IRENA (2019), International Finance Corporation (2015), Fabinyi et al. (2020).



Fig. 5. Initial investment cost of the solar PV farm and HPP

The total initial cost for hydropower projects, according to IRENA (2019), is ~ 1,500 \in /kW for HPP in the range of 101-150 MW of capacity. While based on the preliminary calculation, it was evaluated that the initial cost for a 100 MW solar PV farm is ~ 1,600 \in /kW. Ideally, the costs are comparable for HPP and PV in Kyrgyzstan. But when it comes to sustainability, solar PV farm is a more liable and secure energy generation source in Kyrgyzstan. As Kyrgyzstan falls under the high-seismic zone, the hydropower plants are more vulnerable to the risks. The existing HPP power generation facilities already got affected by frequent earthquakes in Kyrgyzstan and this naturally affect the power output. With the aim of comparing the risk involved in the generation of solar and hydropower in Kyrgyzstan, Tab. 3 states the major impacts of both technologies on the five capitals. Both given systems were considered to be most vulnerable to some particular disasters, given the technology, location and recent examples. This disaster vulnerability is indicated in the right-hand column of Tab. 3. McLellan et al. (2012) use a five-capital framework as the basis of their assessment, with the capitals being described in Tab. 3.

	Hydro	Solar PV
Human	Health (dam break and flash flooding risk)	Health (electrocution risk)
Social	Minimal to major impacts associated with loss of electricity; flooding destruction	Minor impacts associated with loss of electricity
Economic	Minimal to major impacts. Loss of electricity and flooding; Loss of workforce, revenue, consumer base	Minor impacts associated with loss of electricity; Cost of repair could be significantly proportional to supply
Manufactured	Loss of infrastructure by flash flooding	N/A
Natural	Silt and relocated water patterns impact on ecology	N/A
Disaster vulnerability	Earthquake; Severe flooding	Flooding; Tsunami; Gale force winds

1 ab. 5. Major impacts of solar and nyuro chergy systems on the five capitals based on Mellenan et al. (2012)

As reflected in Tab. 3, the highest impacts for the five capitals are related to hydro energy generation. This gives a clear insight into the advantages of solar energy over hydro energy. It is important to highlight that the disaster vulnerability of solar energy systems does not include earthquakes, which are a continuous hazard in Kyrgyzstan due to the presence of high seismic intensity in the area.

4. Discussion

4.1 Viability analysis

The policies and legislation analysis of Kyrgyzstan revealed information regarding energy-related strategies and programs. However, the objectives of many programs were hard to achieve, and some programs requirements could not be implemented or enforced effectively. Implementing electricity tariffs that fully recover the real costs is a prerequisite to achieving the main objective of the strategies. Moreover, the monopoly strategy of the Kyrgyz government and the low FIT (0.03 \notin /kWh for all the RES) result in limited investments in the renewable energy sector. The provisions of the *Law on Renewable Energy Sources* theoretically make the renewable energy sector attractive for investors. Under a FIT, eligible renewable electricity generator / private investors are paid a cost-based price for the renewable electricity they produce. However, the amendment made in July 2019 in FIT reduces the coefficient for all renewable energy sources (0.03 \notin /kWh) (Government of Kyrgyzstan, 2019). Previously (before July 2019), the FIT used to be different for each RE source, and consequently, the highest FIT was provided for solar energy (0.16 \notin /kWh) (Government of Kyrgyzstan, 2019). Certainly, an initial situation before the law's modification was more attractive for investors, especially for those who wanted to invest in the solar sector. Naturally, the current FIT for solar energy of Kyrgyzstan does not bring the economic feasibility that was expected to get, especially considering the great solar PV potential of the country, and there is negligible chance to get any payback for private investors.

4.2 Conceptual framework for bridging the gap between technical potential and market barriers

Kyrgyz power sector suffers from outdated infrastructure and is not capable to fulfil the growing and fluctuating inter-seasonal energy demand. The Kyrgyz electricity users face an irregular supply of electricity as well as fluctuations in voltage because of reduced power production in the winter season. Also, the majority of the hydropower generation facilities are outdated and not capable enough to produce the rated power. The presented article as well as recent theoretical development identified that hydropower development is not favorable in Kyrgyzstan. Further to this, the cold climatic conditions are the key hurdle for reduced power production. Hence, the Kyrgyz power sector is facing the issue of sustainability and availability.

On the contrary, the presented feasibility study identified the great technical potential for solar PV electricity generation in Kyrgyzstan. Identified that integration of renewable energies can bring stability and sustainability to Kyrgyzstan. However, because of the current energy policies as well as the limited market opportunities the solar energy sector is not yet developed. To foster the solar PV development in Kyrgyzstan, the presented article proposed a conceptual framework presented in Fig 6. The framework was developed based on the analysis of the results of the literature review.



Fig. 6: Conceptual framework to foster solar PV in Kyrgyzstan to secure existing power sector

• **Resource pillar:** Kyrgyzstan has a vast silicon resource this has a great opportunity to develop a manufacturing market within the country's territory. Also, because of the special geographical condition, Kyrgyzstan is blessed with more than 300+ solar days. As shown in Fig 1, the solar potential of Kyrgyzstan is 60% higher as compared to European solar potential. In addition to that, the current Kyrgyz power sector has a huge deficit to meet the high and growing demand of Kyrgyzstan. The Kyrgyz power sector already faces a critical issue with the intersessional demand. Hence, there is room for more power production as the country is required it immediately (Kelpšaitė et al., 2018).

• **Legislative pillar:** The policymakers should make the FIT more attractive to invite investors to invest in solar-assisted power generation to expand the RE sector in Kyrgyzstan. Consequently, the government should give preference to promoting solar energy instead of focusing on hydro energy. The absence of the regulatory framework and particular authority in the context of renewable energies does not provide enough knowledge and information to the private investors. Hence, it is necessary to develop a suitable legislative framework (Government of Kyrgyzstan, 2019).

• **Market pillar:** The current solar PV market is not yet developed because the available solar energy is unexploited. There are negligible manufacturers available who are dealing with the manufacturing of solar technologies. This yields a great opportunity for market development. Private consumers, investors, the government can take part in the emerging solar market. Also, Kyrgyzstan has a huge agricultural field and there is a great chance for the agro-PV market.

The above-mentioned pillars are the imperative parameter to decode / understand the complex situation of untapped solar energy and the solar market in Kyrgyzstan. It also provided detailed insight into the current market situation, energy legislative framework and scrutinizes the theoretical (and potential) framework to develop solar PV acceptable in Kyrgyzstan.

4.3. Strategies to foster renewable energy generation

Although FIT usually represents a powerful mechanism to incentive the growth of renewable energy generation, it is believed that this role will reduce shortly, until diminishing completely in some regions except for new technologies. Currently, countries like the UK, Germany, Sweden, Spain, and Netherlands present projects that are being built or are already operating under subsidy-free or near subsidy-free conditions (Clifford Chance, 2018).

According to Sikandar et al. 2021, Research and Development (R&D) have been categorized as an incentive to foster renewable energy generation. R&D can bring promising opportunities for Kyrgyzstan to improve existing -and develop new -technologies. Accordingly, the country could grow the industry of solar panels already developed and eliminate completely the costs of material importing. Given the high solar energy potential of Kyrgyzstan, investing in R&D should represent the first phase to boost renewable energy growth.

Besides the gradual reduction of subsidies for renewable energy generation, the decarbonization target of different industries has developed trends for funding clean energy projects. One of the trends that could be successfully applied to the Kyrgyz energy market is the corporate Power Purchase Agreements (PPAs), where large companies purchase clean energy for their own consumption or trading from renewable energy generators. As it might seem

challenging to get companies involved in long-term commitments for clean energy generation, the benefits of below-market price power cost for businesses with high energy consumption can bring large savings on their energy bills through PPAs. Fixed prices, discounts, and green certificates are in return for taking the risk related with intermittent power production from renewable sources (IRENA, IEA and REN21, 2018).

The Renewable Portfolio Standard (RPS) is a regulatory mechanism that can be implemented in the Kyrgyz power sector to foster renewable energy generation. RPS replaced the FIT system in 2012 in South Korea to build a competitive market in the energy sector. South Korea made 13 large power generation companies raise their renewable energy mix in 12 years gradually through the regulations of RPS. The targets of RPS, meaning the percentage of power generation from renewable sources, are reviewed, and adjusted if necessary, every three years in South Korea (IEA, 2020).

The concept of RPS is applicable not only for independent producers but also for government-owned electricity generation companies, as is the case of the Kyrgyz power sector (Ali et al.,2021). European countries, the USA, China, Australia, India, and many others have supported the policy of RPS with tradable Renewable Energy Certificates (REC). A REC is usually given to a power generator company for each MWh of energy produced from renewable sources. The certificates are often traded between the companies to meet the goals of the RPS determined for the year. In this way, Kyrgyzstan could have a boost to invest in new renewable energy projects in the power sector by compromising the power generator companies to increase their renewable energy mix supported by policies of compliance and enforcement. (IRENA, IEA and REN21, 2018).

4.4. Limitations of the study

The study was the first attempt to demonstrate the potential of a large-scale solar PV farm. From a technical point of view, the results were achieved based on the simulation models. Moreover, to check the economic viability, the presented article approached to perform the comparative economic assessment of hydro and solar. However, there are no common sources are available to acquire the prices for the technologies. The presented values are calculated based on the different sources and have a low tendency to be accurate. Therefore, it is recommended to use the same sources to get an accurate idea about the price. This is the weakness of the presented study and is considered as a scope for future research work. Nevertheless, the performed economic analysis can provide a rough idea to the reader. Even with the limitation, the presented feasibility study was successfully identified great technical potential for large-scale solar PV farm in Kyrgyzstan.

5. Conclusions

Currently, Kyrgyzstan generates 92 % of its electricity from hydropower plants. Nevertheless, the infrastructure of the energy sector is outdated and presents frequent breakdowns, due to the damages in the existing hydropower facilities generated by the frequent earthquakes in the region. Nevertheless, the Government of Kyrgyzstan still focuses on the construction of new hydropower plants close to the seismic areas, with the potential to generate high-risk situations. In response to that, the presented study performs the feasibility study of a large-scale solar PV farm in Kyrgyzstan. The simulation of the PV farm was developed by using the modeling software tool *Polysun*. The results of the simulation displayed great potential for solar energy, especially for a high-altitude region.

The analysis of the economic parameters gave an insight into the economic feasibility of both power systems and, accordingly, demonstrated the advantages of the solar PV farm over the hydropower plant. Likewise, the construction of a new hydropower plant involves more negative environmental impacts and a bigger risk for the community and the neighboring countries. Conclusively, exploiting the solar PV potential of Kyrgyzstan could help to improve the power quality and, thus, stabilize the power sector.

Future research should be directed towards the improvement of the legislation related to renewable energy in Kyrgyzstan. As a recommendation, the current FIT should be increased and differentiated for each renewable energy source and further research should be directed to new strategies to foster energy generation from renewable sources. With the expansion of R&D and other policies, the investment in new projects can become feasible even for government-owned companies. The presented article suggested a new proposal for the FIT of solar energy. The policymakers should make the FIT and other new policies more attractive to invite investors to invest in RE-based power generation to expand the RE sector in Kyrgyzstan. Another recommendation would be that the electricity tariff should be leveled to reflect the real cost of electricity in Kyrgyzstan. With more income and a reasonable FIT, the investment in the renewable energy sector and grid maintenance becomes more profitable and can bridge the gap between technical potential and market barriers in Kyrgyzstan.

6. Acknowledgments

The work presented in this paper was funded by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany within the CLIENT II funding programme International Partnerships for Sustainable Innovations under the project "ÖkoFlussPlan" (Project ID 01LZ1802A-F). The overall aim of ÖkoFlussPlan is to preserve the alluvial forests along the Naryn river and to implement sustainable energy solutions for the local population.

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H-01. Solar Thermal and Hybrid Collectors

Domestic hot water and cooling demand coverage for nearly Zero Energy Buildings applying combined solar heating and radiative cooling

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Abstract

A new device capable to combine night radiative cooling and solar thermal collection (called Radiative Collector and Emitter, RCE) is analyzed to determine its potential to cover the Domestic Hot Water (DHW) and cooling demands for a single-family detached house following nearly Zero Energy Building (nZEB) standards. The energy demand of the considered house is determined by numerical simulations using EnergyPlus and compared to the energy (heat and cold) production of the RCE, determined by Trnsys simulations, in order to identify the potential for demand coverage. Results show best coverages can be achieved for climates Cwb and Csb, as well as BSh of the Köppen-Geiger climate classification, when considering the demand coverage, while the most promising climates are BSh, BSk, and BWh in terms of useful energy production. Further research is warranted to optimize the size of the system in order to identify more climates with significant potential, as well as study other building typologies with different demand profiles.

Keywords: Renewable Heating and Cooling, Radiative Cooling, Solar Thermal Collection, nearly Zero Energy Buildings, Demand Coverage, Polygeneration.

1. Introduction

Radiative cooling is a technology capable to produce cold through the dissipation of heat to the sky taking advantage of the infrared atmospheric window (7-14 µm) (Vall and Castell, 2017). The study of radiative cooling dates back to the 60s, although it has not reached the market, mainly due to its low power density (around 65W/m²) (Berdahl et al., 1983; Ferrer Tevar et al., 2015; Landro et al., 1980). In the last years two new approaches have been studied in order to improve this technology. On the one hand, the use of selective surfaces with nanomaterials (Raman et al., 2014) allows the use of radiative cooling under sunlight conditions; on the other hand, the combination of night radiative cooling with daytime solar collection (the Radiative Collector and Emitter, RCE) (Hu et al., 2016; Vall et al., 2020) allows the production of two thermal products (heat and cold) with the same device. The RCE has a similar structure as that of a solar thermal collector, with a 2 m x 1 m x 80 mm aluminum frame, a metallic absorber painted black with 8 cooper pipes of 8 mm internal diameter and 0.6 mm thick, and 30 mm glass-wool back insulation. An adaptive cover consisting on a transparent 3 mm glass was used as cover for solar collection mode, and a 0.6 mm thick polyethylene (PE) film for radiative cooling was used (Fig. 1). Solar thermal collectors are a technology widely implemented in buildings in order to cover Domestic Hot Water (DHW) demands. However, cooling demands in buildings are commonly covered by non-renewable technologies. Vall et al., 2018 studied the potential energy savings achievable by integrating the RCE into different types of buildings in different climates, showing promising potential in several climates. However, the cooling demands are high compared to the production rates of the RCE, which limits the coverage of the cooling demands. The cold production of the RCE is one order of magnitude lower than the heat production, thus being especially suitable for applications with similar ratios of heat-to-cold demand.

Nearly Zero Energy Buildings (nZEB) are described as buildings that have very high energy performance. The low amount of energy that these buildings require comes mostly from renewable sources. The Energy Performance of Buildings Directive (European Parliament. Directive 2010/31/EU) requires all new buildings to be nearly zero-

energy by the end of 2020. Therefore, it is expected that future trends in building energy demands will follow this tendency. Passive House is a well-known and internationally accepted standard for nZEB, which defines some strategies and key performance indicators to achieve nZEB specific goals.

In this paper the potential for integrating the above mentioned RCE technology in nZEB buildings (considering the heating and cooling demands limitation of Passive House) is studied. Cooling and DHW demand coverage are presented for different climates (Kottek et al., 2006).

2. Methodology

To evaluate the coverage of the cooling and DHW demands by the RCE under different climatic conditions, the energy production of the RCE and the energy demand of the buildings were determined by numerical simulation with Trnsys and EnergyPlus, respectively (see Fig. 2).



Fig. 2: Conceptual scheme of the energy production, demand and coverage calculation

2.1. World climates considered

Different cities representing different world climate zones, based on the Köppen-Geiger classification (Kottek et al., 2006), are analyzed in order to identify the most promising conditions for the RCE technology to cover the DHW and cooling demands. Tab. 1 presents the studied cities, their climate zone and coordinates. EnergyPlus weather files from the selected cities are used for both the simulation of the energy demands of the buildings and the energy production of the RCE system.

Tab. 1: Studied cities, climate zone and coordinates.

	Climatic zone	Latitude	Longitude
Cairo (Egypt)	BWh	30° N	31° E
Lleida (Spain)	BSh	41° N	0° E
Thessalonica (Greece)	BSk	40° N	22 °E
Barcelona (Spain)	Csa	41 °N	2° E
San Francisco (USA)	Csb	37°N	122° W
Johannesburg (South Africa)	Cwb	26° S	28° E
Tokyo (Japan)	Cfa	35° N	139° E

	Climatic zone	Latitude	Longitude
London (United Kingdom)	Cfb	51° N	0°
Pyongyang (North Korea)	Dwa	39° N	125° E
Chicago (USA)	Dfa	41° N	87° W

2.2. Energy Demand

The Domestic Hot Water (DHW) and cooling demand for a single-family detached house (Fig. 3) is determined by numerical simulations carried out in EnergyPlus for different weather climates. The building considered was taken from the USA Department of Energy (DOE), which provides a set of prototype building models to be used in EnergyPlus. Full details of the buildings considered, in terms of envelope, schedules, internal loads, DHW consumption, etc., are presented in (U.S. Department of Energy). A summary of the envelope properties is presented in Tab. 2.



Fig. 3: Single-family detached house model. South and west view.

However, in order to reach nearly Zero Energy Building (nZEB) standards, some additional strategies, both active and passive, are implemented. The building model is considered to fulfill the nZEB standards if the energy demand for heating and for cooling is below 15 kW/m^2 ·year, the thermal transmittance of the external walls is below U_{max} = 0.15 W/m²·K and the infiltrations are below 0.6 ACH, following the standards of Passive House (Passive House Institute, 2015). The strategies implemented are (Tab. 3): cooling set point temperature, increase of thermal insulation (using mineral wool with 0.034 w/m·K), triple glassed windows, fix and movable shadings for the windows, and summer night ventilation.

The different values used for each city are presented in Tab. 4 (U-values), Tab. 5 (fix solar protections), Tab. 6 (mobile solar protections), and Tab. 7 (night ventilation).

	Materials	Thickness [m]	Thermal conductivity [W/m·K]	Thermal resistance [m²·K/W]	U-value [W/m²·K]
	syn_stucco	0.003048	0.086500	0.035237	
FAÇADE	sheating_consol_layer	0.012700	0.094018	0.135080	
	OSB_7/16in	0.011113	0.116300	0.095550	0.359
	wall_consol_layer	0.139700	0.057165	2.443803	
	Drywall_1/2in	0.012700	0.160090	0.079330	
BOOFI	Asphalt_shingle	0.006340	0.081860	0.077448	5 259
ROOF I	OSB_1/2in	0.012700	0.116300	0.109200	3.338
	cement_Stucco	0.019050	0.721000	0.026422	2.421
KOUF II	Bldg_paper_felt	-	-	0.010567	2.431

Tab. 2: Façade, floor, and roof composition of the building.

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	Materials	Thickness [m]	Thermal conductivity [W/m·K]	Thermal resistance [m ² ·K/W]	U-value [W/m²·K]
	OSB_5/8in	0.015875	0.116300	0.136501	
	Air_4_in_vert	-	-	0.158499	
	Drywall_1/2in	0.012700	0.160090	0.079330	
	floor_consol_layer	0.139700	0.049104	2.844988	
FLOOR	Plywood_3/4in	0.019050	0.115458	0.164995	0.291
	Carpet_n_pad	0.025400	0.060131	0.422409	

Tab. 3: Additional strategies implemented in order to reach the nZEB standard.

	Single-family detached house
Wall area (m ²)	221.2
Window area (m ²)	33.2
Window-Wall Ratio [%]	15%
Net Conditioned Area (m ²)	223.1
Roof Area (m ²)	116.4
Additional passive an	d active strategies
Cooling set point temperature (°C)	26
Reduction of the U-value	Included
Triple glassed windows	$U=0.76 \text{ W/m}^2\text{K}$
Infiltrations	Reduction of 40% of the infiltration area
Summer night ventilation	Included
Ventilation heat recovery	75%
Solar protection	Included

Tab. 4. Thermal transmittance of the envelope for each studied city.

	UFAÇADES [W/m ² ·K]	UFLOOR[W/m ² ·K]	UROOF [W/m ² ·K]
Cairo (Egypt)	0.1092	0.3690	0.08367
Lleida (Spain)	0.1237	0.1146	0.1277
Thessalonica (Greece)	0.1389	0.1275	0.1439
Barcelona (Spain)	0.1389	0.1275	0.1439
San Francisco (USA)	0.1389	0.1275	0.1439
Johannesburg (South Africa)	0.1389	0.1275	0.1439
Tokyo (Japan)	0.1389	0.1275	0.1439
London (United Kingdom)	0.1389	0.1275	0.1439
Pyongyang (North Korea)	0.1389	0.1275	0.1439

	U _{FAÇADES} [W/m ² ·K]	U _{FLOOR} [W/m ² ·K]	U _{ROOF} [W/m ² ·K]
Chicago (USA)	0.08611	0.08159	0.09541

		Latitude	North [m]	South [m]	East [m]	West [m]
Coire (Equat)	Depth	200 N	0.2	0.9	1.9	1.9
Cairo (Egypt)	Width*	50 N	0	2	0	0
Lleida (Spain)		41° N	0.2	0.6	1.9	1.9
Thessalonica (Greece)		40° N	0.2	0.6	1.9	1.9
Barcelona (Spain)		41 °N	0.2	0.6	1.9	1.9
San Francisco (USA)		37°N	0.2	0.45	1.9	1.9
Johannesburg (South Africa)		26° S	0.6	0.2	1.9	1.9
Tokyo	(Japan)	35° N	0.2	0.45	1.9	1.9
London (Unit	ed Kingdom)	51° N	0.2	0.8	1	1
Pyongyang (North Korea)	39° N	0.2	0.6	1.9	1.9
Chicago	o (USA)	41° N	0,2	0.6	1.9	1.9

Tab. 5. Depth of the fix solar protections for each orientation and for each studied city.

*Additional width of the fix solar protections respect to the window width.

Tab. 6. Schedule for mobile solar protections.

	Schedule	Covered window area [%]			
Cairo (Egypt)	Always	90			
Lleida (Spain)	From 1/06 to 31/08	70			
Thessalonica (Greece)	From 1/06 to 31/08 70				
Barcelona (Spain)	1) From 1/06 to 31/08				
San Francisco (USA)	- Never -				
Johannesburg (South Africa)	From 21/09 to 30/04	85			
Tokyo (Japan)	From 1/06 to 30/09	70			
London (United Kingdom)	- Ne	vver -			
Pyongyang (North Korea)	From 1/06 to 30/09	70			
Chicago (USA)	From 22/06 to 31/08	80			

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	Schedule	Period	Air changes per hour
Cairo (Egypt)	From 1/04 to 30/11	From 21 to 7	10 ACH
Lleida (Spain)	From 21/06 to 30/09	From 22 to 9	10 ACH
Thessalonica (Greece)	From 16/05 to 30/09	From 22 to 9	10 ACH
Barcelona (Spain)	From 21/06 to 30/09	From 22 to 9	10 ACH
San Francisco (USA)	From 21/06 to 30/09	From 22 to 9	10 ACH
Johannesburg (South Africa)	From 1/10 to 20/03	From 22 to 9	10 ACH
Tokyo (Japan)	From 1/06 to 31/10	From 20 to 7	10 ACH
London (United Kingdom)	From 21/06 to 30/09	From 22 to 9	10 ACH
Pyongyang (North Korea)	From 21/06 to 30/09	From 22 to 9	10 ACH
Chicago (USA)	From 22/06 to 31/08	From 22 to 9	10 ACH

Tab. 7. Night ventilation conditions.

To determine the DHW demand, the schedules considered in the model are used (with the exception for the showers, which are considered with no consumption during night). The consumers considered are presented in Tab. 8.

Tab. 8. Consumers considered	d for the Domestic Ho	ot Water demand calculation.
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Consumer	Capacity	Water consumption	Duration	Flow rate
Washing machine	7 kg	42 to 47 L	1h 30 min	28 to 31 L/h
Dishwasher	13 uses	6.5 to 7 L	3h (eco)	2.2 to 2.4 L/h

2.3. Energy production

The energy production of the RCE is determined by numerical simulation in Trnsys. A numerical model of the RCE developed by Vall et al., 2020 is used and integrated into a system with thermal energy storage for both heat and cold (Fig. 4). The numerical model discretizes the RCE in several nodes using one dimensional (1D) relations based on an electrical analogy. The heat balance equations are first order ordinary differential equations in time, which are solved using backward Euler method (or implicit Euler method), and the Gauss-Seidel iterative method. The model was experimentally validated for both solar heating and radiative cooling modes, showing a good accuracy (Vall et al., 2020).

The DHW and cooling demand obtained from the EnergyPlus simulations are introduced in the model in order to determine the demand coverage achieved with the RCE system. The RCE field considered has 10 m^2 (consisting of 5 RCE panels of 2 m² each) of surface and it is connected to a hot water tank of 0.6 m³ and a cold water tank of 1 m³.

The RCE operates under solar collection mode during daytime, and under radiative cooling mode during nighttime, with a flow rate of 576 kg/h.

Once both the demands and productions are calculated, the coverage achieved by the RCE system must be determined.



Fig. 4: Conceptual scheme of the RCE system and its link to the building demand.

2.4. Demand coverage

To determine the DHW demand coverage, the temperature of the DHW consumed is considered to be at 45°C, while the fresh water refilling the tank is considered to be at 13°C. The DHW demand coverage is determined as the ratio between the energy provided by the hot water tank to reach the DHW temperature level and flow rate required and the DHW demand determined by the EnergyPlus model.

To determine the cooling demand coverage, the energy provided by the cold water tank is calculated considering the temperature difference between the cold water and the building ambient temperature, and adjusting the flow rate to meet the demand from EnergyPlus simulations. Then, the cooling demand coverage is determined as the ratio between the energy provided by the cold water tank and the cooling demand determined by the EnergyPlus model.

3. Results

3.1. Energy demand for nZEB

Based on simulations on EnergyPlus, the cooling and heating demands for each city are presented in Tab. 9, reaching nZEB standards. Cooling demands are in the range 0.3-5 kWh/m²·year, with the exception of Cairo, that reaches a cooling demand of almost 13 kWh/m²·year. On the other hand, heating demands are in the range of 0.3-5.5 kWh/m²·year, with the exceptions of London, Pyongyang, and Chicago, with heating demands of 7.5 kWh/m²·year, 13.5 kWh/m²·year, and 14.3 kWh/m²·year, respectively.

Гab.	9.	Cooling	and	heating	demand	for	each	studied	city.
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	Cooling demand [kWh/m²·year]	Heating demand [kWh/m²·year]
Cairo (Egypt)	12.76	0.28
Lleida (Spain)	3.33	4.19
Thessalonica (Greece)	4.91	3.10
Barcelona (Spain)	2.30	1.38
San Francisco (USA)	0.28	0.16
Johannesburg (South Africa)	0.41	0.26
Tokyo (Japan)	3.18	5.51
London (United Kingdom)	0.34	7.49
Pyongyang (North Korea)	2.72	13.50
Chicago (USA)	4.13	14.28

3.2. Domestic hot water demand coverage

Tab. 10 presents the annual DHW demand and the annual DHW demand covered by the RCE. It can be seen that in every city, the annual DHW demand is very similar, around 3,200 kWh/year. On the other hand, the percentage of DHW demand covered by the RCE changes depending on the location and climate. As it can be seen in Fig. 5, the cities with a higher DHW demand coverage are Johannesburg and Cairo, with values around 90% and 86%, respectively. The cities with lowest coverage are London and Chicago, covering only 42% and 57% of the demand respectively. The other studied cities present coverages between 60-75%.

	DHW demand [kWh/year]	DHW demand covered by RCE [kWh/year]	DHW demand covered by RCE [%]
Cairo (Egypt)	3,214	2,756	85.7
Lleida (Spain)	3,227	2,217	68.7
Thessalonica (Greece)	3,226	2,210	68.5
Barcelona (Spain)	3,223	2,179	67.6
San Francisco (USA)	3,218	2,422	75.3
Johannesburg (South Africa)	3,210	2,885	89.9
Tokyo (Japan)	3,229	2,139	66.2
London (United Kingdom)	3,236	1,368	42.3
Pyongyang (North Korea)	3,229	1,969	61.0
Chicago (USA)	3,230	1,851	57.3

	Tab.	10.	Annual	Domestic	Hot	Water	demand	and	coverage	by	RCE.
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3.3. Cooling demand coverage

Tab. 11 presents the annual cooling demand and the annual cooling demand covered by the RCE. It can be seen that, only in those cities with very low cooling demands it can be fully covered by the RCE system (10 m²). However, again London is an exception, with a very low cooling demand (76 kWh/year) but with low coverage (41%) due to its low production.

As it can be seen in Fig. 5, the cities with higher cooling demand coverage are Johannesburg and San Francisco, covering all the cooling demand. The cities with lowest coverage are Cairo, Tokyo, and Pyongyang, covering only 8%, 12%, and 16% of the demand, respectively. Chicago, Thessalonica, and Barcelona present coverages around 23-24%, while London and Lleida reach values of 41% and 47%, respectively.

Гаb. 11. Annua	l cooling	demand	and	coverage	by	RCE.
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	Cooling demand [kWh/year]	Cooling demand covered by RCE [kWh/year]	Cooling demand covered by RCE [%]
Cairo (Egypt)	2,817	223	7.9
Lleida (Spain)	736	348	47.3
Thessalonica (Greece)	1,084	248	22.9
Barcelona (Spain)	508	124	24.4
San Francisco (USA)	61	61	100.0

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	Cooling demand [kWh/year]	Cooling demand covered by RCE [kWh/year]	Cooling demand covered by RCE [%]
Johannesburg (South Africa)	90	90	100.0
Tokyo (Japan)	701	84	12.0
London (United Kingdom)	76	31	40.8
Pyongyang (North Korea)	601	98	16.3
Chicago (USA)	911	208	22.8

It must be highlighted that the cooling demand is very weather dependent, and it can be very seasonal in some climates, while in other ones the cooling period can be longer. This significantly affects the cooling energy produced by the RCE that can be used. Locations where the cooling period is short may not use the energy produced by the RCE most of the year, not taking advantage of the full potential of the RCE. On the other hand, locations with longer cooling periods may use more energy produced by the RCE. Thus, locations with lower coverage values may present high production and use of cooling energy by the RCE. This is the case of Cairo, where the coverage percentage is the lowest (7.9%), while the energy production is the third one (223 kWh/year), after Lleida and Thessalonica. In these cases, although the coverage values are low, the energy savings can be significant.



Fig. 5: Domestic Hot Water and cooling demand coverage for each studied city.

3.4. Climate effect

In order to determine the effect of the ambient humidity in the cooling demand covered by the RCE, a comparison between Lleida and Barcelona cities is presented. These cities are 130 km far away, thus presenting similar seasons and sunlight hours. However, significant differences are observed in terms of humidity during summer (Tab. 12).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lleida (Spain)	74%	64%	57%	55%	51%	45%	45%	49%	57%	65%	71%	75%
Barcelona (Spain)	79%	76%	74%	75%	74%	72%	70%	72%	77%	80%	79%	79%

Tab. 12. Ambient humidity for the cities of Lleida and Barcelona.



Fig. 6: Comparison of the cooling demand covered by the RCE and the ambient humidity between Lleida and Barcelona.

Fig. 6 shows that the cooling demand coverage during summer months in Lleida is significantly higher than that in Barcelona, although the cooling demand is lower in Barcelona. The higher humidity in Barcelona affects the dew point temperature, thus affecting the effective sky emissivity, which is critical for radiative cooling. This demonstrates the effect of the ambient humidity in the radiative cooling production. Therefore, climates with low humidity are preferred for radiative cooling implementation.

3.5. Suitable climates

In order to identify the most suitable climates for the RCE technology to be implemented in single-family detached houses, a minimum DHW coverage of 60% and a minimum cooling coverage of 40% are stablished. Based on these criteria, the most suitable cases are Johannesburg (DHW coverage of 89.9% and cooling coverage of 100%), San Francisco (DHW coverage of 75.3% and cooling coverage of 100%), and Lleida (DHW coverage of 68.7% and cooling coverage of 47.3%), representing climates Cwb, Csb, and BSh, respectively.

On the other hand, considering a criterion based on the energy production (minimum of 2,000 kWh/year of DHW and of 200 kWh/year of cooling), the most suitable cases are Lleida, Thessalonica, and Cairo, representing climates BSh, BSk, and BWh, respectively.

As it can be seen, only Lleida, representing climate BSh, fulfills both criteria.

These results are limited to the case of 10 m^2 of RCE. Higher RCE surfaces would lead to different results and could result in more climates with significant potential for the RCE implementation.

4. Conclusions

The potential of a novel renewable heating and cooling technology (RCE) to cover the Domestic Hot Water and cooling demands of a single-family detached house achieving nearly Zero Energy Building standards has been studied. The climates Cwb and Csb of the Köppen-Geiger climate classification are the ones showing more promising results in terms of demand coverage, followed by climate BSh. In terms of useful energy production, climates BSh, BSk, and BWh are the most promising ones.

In order to identify new opportunities and to determine the most suitable climates for the RCE implementation, other building typologies must be studied, especially those with different demand profiles.

Higher RCE surfaces could increase the energy production and coverage; thus, an optimization analysis of the RCE surface to be implemented for each city/climate is of high interest.

5. Acknowledgments

This publication is part of the R+D+i project RTI2018-097669-A-I00, funded by MCIN/ AEI/10.13039/501100011033/ y FEDER "Una manera de hacer Europa". The work was partially funded by the Catalan Government under grant agreement 2017 SGR 659. Marta Delgado wants to thank Ministerio de

Educación y Formación Profesional for her scholarship (BECA-COLABORACIÓN 2020/2021).

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Experimental investigation of a new turbocharged concentrating solar air heater

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Abstract

Although still uncommon, direct air heating inside a linear concentrating collector can be a suitable solution for industrial hot air production aiming at environmental sustainability and decarbonization. In order to demonstrate the technical feasibility and investigating the key features of the technology, an experimental prototype is installed and tested. A small-scale solar field with 79.2 m^2 of linear Fresnel collectors is coupled with an automotive turbocharger to reduce the pumping power in an innovative layout. A compressor increases air pressure before it is heated up to 450 - 500 °C inside evacuated receivers. The turbine recovers the compressing power. Hot air at 300 - 400 °C is provided at the turbine exit, available for usage. Results enable the characterization of the main components and system behavior, establishing critical design and operational aspects.

Solar air heater; linear Fresnel collector; Solar heat for industrial processes; Industrial drying

1. Introduction

The use of air as heat, moisture and other vapor carrying fluid is widespread in the industry. Drying and thermal curing are high energy demanding processes requiring hot air, which is common to several industrial sectors, including agricultural, food and beverage, pharmaceutical, mining, wastewater and residues treatment, manufacturing, among others. Process hot air at low and medium temperatures is currently provided from fossil fuel combustion as well as from electricity, which has only a partial renewable energy share. Solar thermal energy has great potential as an alternative source, aiming at decreased pollution and decarbonization. Air solar collectors can heat ambient air up to ~100 °C without the need for a primary heat transfer fluid HTF. For applications requiring higher temperatures, linear concentrating collectors are a suitable alternative to conventional air heating systems. Both linear Fresnel collector LFC and parabolic trough collector PTC have been considered for industrial indirect hot air production above 150 °C, as reported by (Farjana *et al.*, 2018) and (SHIP Database). Some experimental research was performed by (Zahler and Iglauer, 2012) and (Rehman

et al., 2019). These solutions require a proper primary HTF, such as thermal oil or pressurized water, for heat evacuation from the collector receiver and downstream delivery to process air through an HTF/air heat exchanger HX.

Direct solar air heating in concentrating collectors would avoid the use of HTFs and HXs and their related costs, risk of spillage, and maintenance, although, their use is still uncommon. (Famiglietti *et al.*, 2020) indicates that the main drawback of direct solar air heating in concentrating collectors using conventional evacuated receivers is the high pumping power requirement, due to low thermal diffusivity and high kinematic viscosity, besides the overheating risk of receiver tube due to low internal heat transfer rate. They proposed an innovative turbo-assisted solar air heater T-SAH, involving an automotive turbocharger to mitigate these drawbacks. The compressor increases the air density in the receiver, reducing flow velocity and stagnation pressure drops. Meanwhile a turbine provides compressing and pumping power, avoiding the external auxiliary energy consumption. This enables higher air mass flow rate, thus preventing the receiver overheating risk. These authors demonstrate that hot air up to 300 - 400 °C can be provided at the turbine outlet. The concept of turbo-assisted solar air heater T-SAH is further investigated numerically by (Famiglietti *et al.*, 2021) simulating a medium-scale solar field of linear Fresnel collectors coupled with a commercial automotive turbocharger. The present work summarizes the main experimental results obtained from an original prototype of the T-SAH described in Section 2, using a 79.2 m² of linear Fresnel collectors and a small off-the-shelf turbocharger.

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2. Experimental setup

The prototype of a turbocharged concentrating solar air heater was installed on the rooftop of Carlos III University of Madrid (Spain), in the city of Leganés. Fig.1 shows its layout.



Fig.1: Experimental setup of T-SAH installed at Carlos III University of Madrid, Linear Fresnel Collector LFC, auxiliary compressor ac, turbo-compressor c, turbine e, post-heating unit ph.

The solar field consists of three linear Fresnel collectors LFCs installed in series, equipped with five standard evacuated tubes. The LFC is the first generation of a commercial module developed and manufactured by (SolatomTM). The primary reflector is composed by 10 curved mirrors of $w_m = 0.50$ m aperture, rotated around horizontal axis with individual tracking motors. The secondary reflector has trapezoidal shape and aims to recover the concentrated irradiance missing the receiver. An original feature of the collector is foldability. The primary reflector structure is made of two foldable wings. In addition, the secondary receiver includes a mechanism for sliding it up and down. When folded and closed, the collector is containerized into a rectangular-shaped box and can be easily transported. The module is pre-assembled in the factory and transported to the installation place already calibrated and tuned. Fig. 2(a) shows a downstream view the solar field tracking the sun.

The receiver is of the single tube type and consists of standard evacuated tubes manufactured by (Archimede Solar EnergyTM), originally developed for thermal oil HTF (model HCEOI-12). The stainless-steel tube having external diameter of $D_{ex} = 70$ mm is covered by selective coating and embed into a concentric vacuum glass tube of high transparency. The selective coating has a maximum operating temperature of 580 °C and a maximum allowable temperature of 600 °C.



Fig. 2. Experimental installation at Carlos III University of Madrid, Leganés (Spain). (a) Downstream view of the solar field on tracking, primary and secondary reflector, and receiver tubes, (b) turbocharger (before thermal insulation).

The required air temperatures inside the receiver induce high receiver temperatures and a consequent nonnegligible axial thermal dilatation. Considering the thermal linear expansion coefficient of stainless steel of $0.016 \frac{\text{mm}}{\text{m K}}$, dilatation over the total tube length $L_t = 20 \text{ m}$ is estimated between 100 mm and 200 mm. Accordingly, receiver tubes have been provided with sliding support brackets, avoiding mechanical stress and compression buckling, Fig.2. The dilatation of the receiver with respect to the glass cover evacuated tube is compensated by bellows according to the receiver manufacturer's design.



Fig.3. Schematic of sliding junction between consecutive receiver tubes

An automotive journal bearings turbocharger (GT1544 (Garrett Advancing Motion)) has been connected to the receiver through thermally insulated piping, Fig.2(b). The compressor wheel has a diameter of $D_c = 43.9$ mm, with a TRIM (the ratio between smallest and highest wheel area) of 56%. The turbine has a wheel diameter is $D_e = 41$ mm and TRIM of 58%. Two parallel electrical blowers (Elektor SD22 FU 80/1,1) are installed in series with the turbocompressor, controlled by a variable frequency converter (Lense 8200 vector) as an auxiliary source of power.

An auxiliary post-heating unit has been provided for additional experimentation. They were mounted downstream of the solar collectors to further increase the inlet turbine temperature according to the experimental tests devised. It is made of electrical resistances with a limiting temperature of 650 - 700°C able to generate 8 kW of thermal power.

The set-up is instrumented by placing Type K thermocouples class A and pressure sensors in several points of the air circuit, according to Fig.1, with an estimated uncertainty of ± 2.0 °C and ± 25 mbar respectively. Airflow is measured at the inlet using a sensor having an uncertainty of $\pm 3\%$ (Schmidt 30.015 MPM). Rotational turbocharger speed is measured by an optical speed sensor with +/-0.05% uncertainty. Two pyranometers (Kipp & Zonen) with $\pm 3\%$ total uncertainty measure global solar irradiance G_{glo} on the horizontal plane and diffuse irradiance G_d . Monitoring and data acquisition with a time interval of 30 s was enabled by a dedicated SCADA, implemented in a Programmable Logic Controller PLC (Unitronic USP-104-B10). Tab.1 reports relevant prototype parameters.

Table 1. Prototype parameters.					
LFC active length	L _m	5.28 m	Overall receiver length	L_r	20.65 m
LFC aperture width	Wa	5.00 m	Receiver internal diameter	D	0.066 m
Height receiver	H _m	2.72 m	Overall active area	$n_s A_m$	79.2 m ²
LFC active area	A _m	26.40 m ²	Connection pipe 1	L_{n1}	26 m
Normal optical efficiency	η_{op0}	0.632	Connection pipe 2	L _{n2}	3 m
Mirrors per module	n _m	10	Connection internal diam.	D _n	0.08m
Mirror aperture width	Wm	0.50 m	Orientation (0 = South)	γ _r	54.3 deg W
LFC in series	n _s	3	Latitude	Φ_{loc}	40.165 deg N
Max. temperature receiver	T _{w,max}	600°C	Longitude	λ_{loc}	3.704 deg W

Table 1. Prototype parameters.

3. Results

Several tests have been carried out on the T-SAH prototype, described in Section 2 aiming at the full characterization of the innovative T-SAH concept. The first one was conducted by running the prototype across a summer day with a clear sky. Solar air heating was performed in the best conditions to reach maximum solar power and air temperature at the receiver outlet, without the post-heating power aid. This allows studying the global behavior of the system, including the solar field, the turbocharger, and the auxiliary compressor. A second representative test, also performed during summer and clear sky conditions, was devised for the turbocharger characterization. The additional thermal power delivered by the post-heater allows increasing the turbocharger testing range, due to higher inlet turbine temperature. This way, additional solar aperture area can be simulated.

Fig. 4 reports the experimental results obtained during the first representative test. During the clear summer day, the turbocharger is accelerated through the auxiliary electrical blowers and three solar collectors are in sun-tracking mode. The post-heating unit is OFF. A thermal transient is established during the first hour of operation, due to piping and receiver tube thermal inertia. Then, quasi-steady-state conditions are achieved, with the turbocharger speed varying slightly with outlet receiver temperature. Fig.4(a) shows the main temperatures across the True Solar Time TST. The peak air temperature at the receiver outlet $T_{3r} > 500$ °C is reached at solar midday. At the compressor outlet air holds a temperature 80 °C < T_2 < 130 °C, according to the increased pressure. Air is delivered at the turbine outlet at 300 °C < T_4 <400 °C. The pressure inside the receiver tubes, which is imposed by the turbocharger varies across the TST up to 1.4 bar, as shown in Fig.4(b). Air mass flow rate \dot{m}_a also varies according to turbocharger speed, Fig. 4(c). Fig. 4(d) depicts the main power contributions. Solar power delivered to airflow in the receiver reaches 17 kW at solar midday \dot{Q}_u , while the thermal power at the outlet air flow \dot{Q}_a is affected by the thermal losses in the sending and return piping \dot{Q}_{n1} and \dot{Q}_{n2} .

The over-pressure imposed by the auxiliary blower decreases as turbocharger speed increases, Fig. 4(b).

$\dot{Q}_u =$	$(T_{3r}c_{p3r} -$	$T_{2r}c_{p2r})\dot{m}_a$	(eq.1)
	< 0. po.	2. p2. , a	

$Q_a = (T_4 c_{p4} - T_{amb} c_{pamb})$	$() \dot{m}_a$	(eq.2)
· · · · · · · · · · · · · · · · · · ·		

$$\dot{Q}_{n1} = (T_2 c_{p2} - T_{2r} c_{p2r}) \, \dot{m}_a \tag{eq.3}$$

$$\dot{Q}_{n2} = (T_{3r}c_{p3r} - T_3c_{p3})\,\dot{m}_a \tag{eq.4}$$



Fig.4. Experimental results, T-SAH operation along a sunny summer day, experimental post-heating OFF, vs. true solar time. (a) Temperatures. (b) Pressures. (c) Mass flow rate and rotating speed. (d) Thermal powers.

The experiment demonstrates the feasibility of direct air heating inside a linear Fresnel collector at moderate pressure, not previously documented in the open literature. Due to the low heat capacity of air, 500 °C of temperature can be reached even in small collector rows as the present one. According to the technical literature, excessive receiver tube bending is recognized as a risk of glass cover breakage, when the tube lateral displacement makes it touch the cover glass tube. This is effect is expected to be a relevant issue when the evacuated tube operated with low internal heat transfer, typical of gaseous flows and with non-uniform circumferential heat flux distribution, which results from the optical concentration either in LFCs and PTCs. In the present experiment, bending has been observed, especially during the starting transient when tubes still encompass circumferential temperature homogenization. Nevertheless, no damage to the cover glass occurred. Secondary reflector with trapezoidal as in the present setup, or more performing ones as compound parabolic

optics, seems beneficial for distributing the solar heat flux across the receiver perimeter, reducing the tube bending.

The direct air heating using the present setup has been further analyzed by the authors in (Famiglietti and Lecuona, 2021b). In that study, either static and dynamic receiver numerical models of the solar field and receiver tube are validated against experimental data from transient heating and cooling tests devised for this purpose. Linear Fresnel collector operation is there analyzed, obtaining an experimental estimation of the optical efficiency. In addition, experimental correction factors for the optical efficiency are proposed for improving the accuracy of the optical performance prediction of the specific LFC employed, although the methodology implemented holds general validity.

Regarding the turbocharger behavior and the pumping power consumption in the present setup, some considerations can be formulated from the experiments overview. According to the original T-SAH concept, the turbocharger increased the air pressure into the T-SAH tubes, recovering compressing power through the turbine. The auxiliary compressor is supposed to be needed only for the starting transient and bypassed once steady-state condition would be reached. Moreover, in the above experiment, it was needed to sustain the turbocharger freewheeling under the operating steady-state conditions tested. The too small turbocharger limits compressor and turbine efficiencies, which in this case have modest values owing to the small size. In addition, due to the relatively small scale of the solar field, the turbocharger does not operate under optimal conditions, being large in size for the mass flow employed.

Nevertheless, the beneficial effect of turbocharging on auxiliary pumping power reduction can be deduced by observing Fig.4. As the turbocharger speed and pressure ratio increase, the overpressure $p_{1t} - p_{0t}$ imposed by the auxiliary compressor decreases slightly. In a T-SAH with higher performances, expected when scaling up to industrial sizes, $p_{1t} = p_{0t}$ would be reached in steady-state conditions, as numerically demonstrated by (Famiglietti *et al.*, 2021).

Within the limited performances of the present experimental setup, a more significant auxiliary over-pressure reduction trend is observed in the second test presented as follows. There, higher inlet turbine temperatures are obtained with the aid of an electrical post-heating unit, Fig.1. The three Fresnel modules were in tracking mode throughout the experiment. The auxiliary compressor was active. The experimental post-heating unit was activated during the experiment with increasing electrical power, delivering an additional thermal power to air \dot{Q}_{ph} . The use of an electrical post-heating unit downstream the solar tube allowed achieving a higher turbine inlet enthalpy, in this case by increasing temperature, without the risk of receiver tube overheating, hence extending the turbocharger testing range without a larger solar facility neither a smaller turbocharger, which would be even less efficient.

The use of electrical post-heating is only for experimental purposes, extending the turbocharger testing range, and would not be implemented in a real industrial plant, being not convenient to dissipate electricity into heat. Fig.5 reports results. An inlet turbine temperature $T_3 = 570$ °C is reached, while the receiver outlet temperature remains at 430 °C as maximum, Fig.5(a). The increased turbine power brings the turbocharger to higher speed and a better operating condition, pumping slightly greater air mass flow rate, Fig.5(b). Despite this, the pressure drop across the receiver tubes drops thanks to the effect of increased pressure, which goes up to 1.6 bar, Fig. 5(c). As mentioned, the reduction of auxiliary overpressure $p_{1t} - p_{0t}$ required decrease with turbocharger speed and inlet turbine temperature, and it is more significant than in the previous case.

A deep analysis of turbocharger performance in the present setup is presented by the authors in (Famiglietti and Lecuona, 2021a). It includes both the adiabatic and diabatic behaviors of the turbocharger under the operating conditions achieved within the proposed T-SAH layout. Experimental 'hot' test performances obtained have been contrasted with the 'cold' performances predicted using extrapolation of the manufacturer's maps, allowing to quantify the parasitic heat transfer phenomena according to a simplified modeling. The analysis shows how the small turbocharger used is affected by thermal losses to ambient and to lubrication oil which downgrades its performance. Such diabatic behavior is expected to be negligible in well-insulated, ball bearings, larger size turbochargers which would be used in industrial-scale plants, as those simulated in (Famiglietti *et al.*, 2021). They further discuss the auxiliary compressor behavior and underpins the critical aspect for scaling up the technology.

Globally, the experimental results reported in the present study show the behavior of a small-scale T-SAH allowing its characterization under real ambient conditions, underpinning critical aspects and possible improvements. The experimental data acquired allows the numerical model validation and tuning, preparing the scaling-up studies carried out in the following.

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Fig. 5. Experimental results, T-SAH operation along a sunny summer day, experimental post-heating unit ON, vs. true solar time. (a) Temperatures. (b) Mass flow rate and speed. (c) Pressures. (d) Thermal powers.

4. Conclusions

The analysis of collected data sets allows scrutinizing several aspects of the installation and original concept of T-SAH. The results indicate the feasibility of direct solar air heating inside standard evacuated tubes up to

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500 °C. Low internal heat transfer, established according to air thermal properties and mass flow rate, combined with the inhomogeneous circumferential distribution of concentrated heat flux, induce tube bending which can cause glass cover contact, if excessive. Receiver tube bending is noticed during the experiments at high temperatures as well as during transient heating. Nevertheless, no damage to the receiver has been detected.

Outlet turbine temperatures between 300 and 400°C have been reached, according to the purpose of the technology and theoretical predictions. The behavior of the turbocharger and auxiliary blower has been investigated. The small-scale facility did not allow to reach optimum operating conditions in the implementation here considered, due to low turbocharger efficiency, typical of small size turbochargers. Nevertheless, the analysis carried out indicates the relevant features of the system when scaled up to typical sizes.

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Mathematical Modeling and Experimental Validation of a Highly Efficient Flat Plate Solar Collector with compound Transparent Insulation Materials including a Silica Layer

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Abstract

The present work consists in the development of a highly efficient solar thermal flat plate solar collector [FPC] with transparent insulation materials [TIM] at high-temperature ranges (η at Δ T/G close to 0.1 Km²/W). The emphasis of the research is set on determining the combination of insulation materials that can boost the overall efficiency at a reasonable cost. Thus, to assess the proportions of honeycomb and granulate silica aerogel layers. A collector without a high-temperature protection system is targeted regarding the previous versions. Additionally, a fast mathematical model is being developed to predict the collector's efficiency with a high degree of confidence with low computational effort based on parallel object-oriented simulation tools. The design is tested experimentally to prove the increment in its efficiency but does not fully protect the TIM layer of 7.5cm since temperatures are estimated to reach above 165°C in stagnation conditions. In contrast, the thickest layer of silica simulated of 3cm decreases the temperature reached in the TIM layer by a Δ T of 30K. Thus, a overheating protection systems appears to be mandatory in any case. The experience obtained will be used to improve the next generation prototype.

Keywords: Flat plate solar collector, thermal insulation materials, silica aerogel, honeycomb

1. Introduction

FPCs have important advantages in respect to other solar collectors due to their cost-effectiveness and robustness. However, they suffer from low efficiencies working at high water inlet temperatures in cold climates compared to tubular vacuum insulated collectors. The research aims to prove that it is possible to achieve high efficiencies under the mentioned climatic conditions using a FPC.

The FPC design in the present work is based on a standard 2 m^2 surface area with a selective absorber. However, the proposed FPC has several more layers than the typical flat-plate collector. In order, from top to bottom, it has a high transmittance and low emissivity glass cover; A layer of cellulose triacetate honeycomb; Another glass layer identical to the cover layer; A layer of granular silica aerogel that has hydrophobic properties and high transmissivity in the visual spectrum and low transmissivity for infrared radiation; A selective absorber based on vertical raisers; An air gap and the back insulation (polyurethane). A graphical representation is presented in Fig. 1.

Yet the design should achieve improved efficiencies at low ambient temperatures and high inlet temperatures ($\eta \text{ at } \Delta T/G \text{ close to } 0.1 \text{ Km}^2/W$), it needs to stand high ambient temperatures and stagnation conditions. The critical point of the FPC is the honeycomb layer since this layer can be damaged if the temperatures reach a threshold. To preserve the properties of the honeycomb, the temperatures that this layer should stand should be under the range of 100°C, the lower, the better, but never above 130-140°C in which severe deterioration takes place as demonstrated by Giovannetti (Giovannetti et al. 2011).

In previous studies, Kessentini (Kessentini, 2014) implemented a low-cost overheating protection system that reduces the absorber temperature then the temperature of the FPC reaches a dangerous temperature. The overheating system consisted of a channel with a thermal spring-activated door. The TIGI's commercial collector followed a more expensive approach with its overheating protection system based on heat pipes (Klier
et al. 2014). Nevertheless, the solution has drawbacks because the efficiency after the high-temperature threshold gets reduced significantly to protect the FPC.

The proposed design implements the transparent granulated silica aerogel layer to insulate and protect the honeycomb layer from the absorber temperatures while boosting the performance of the overall FPC.



Fig. 1: Schematic representation of the FPC with transparent insulation materials (honeycomb and silica aerogel).

2. Mathematical and numerical method

One of the research objectives is to find the optimum layers' thickness or at least the best possible trade-off to maximize efficiency while keeping the costs low. Developing this process only by experimental procedures is not cost-effective; therefore, a simulation tool is required to optimize the design. Additionally, since several simulations are needed to find the optimum configuration, a fast simulation method is preferred.



Fig. 2: Representation of heat transfer and variables for each layer

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A model was implemented in a parallel object-oriented numerical platform (NEST) (Kessentini, 2014) to achieve readability and computing efficiency. The preferred mathematical approach is one-dimensional (considering the mean temperature of the layer), which assumes that each layer of material has two unique temperatures (top and bottom). The fin efficiency approach is followed to calculate the temperatures in the absorber. For the simulation of the radiation flux within the layers of the FPC, the radiosities method (Eckert Drake, 1971) is used. Since the different layers have different visible and infrared spectrum behavior, these radiations are computed separately. In that way, the properties of the honeycomb and silica layers are captured. To analyze the radiation in the model, a virtual void must be created between the layers to allow the radiosities to be computed. The heat balances in each layer are arranged to provide a system of equations. Finally, the overall heat loss coefficient is calculated, and the efficiency is estimated. Inspect Fig. 2. as a representation of the heat transfer variables considered for the calculation.

Notice that each material layer has two temperatures, the external temperature and the internal temperature, which refer to them following the logic of closer to the absorber (interior, int) or further away from it (exterior, ext). The infrared radiation heat transfer is identified with the suffix t and the visible spectrum heat transfer radiation with the suffix s. The overall heat transfer computed by the radiosities method is determined by the suffix rad, and the *trans* suffix identifies the transferred heat transfer radiation. Finally, the conduction and convection heat transfer is identified by the *cond* and *conv* suffixes.

2.1. Heat balances

To obtain the temperature values in each surface of the solar collector, it is necessary to solve a system of equations iteratively. In the current paper, three different cases (layers 1, 2, and 3) will be explained in fine detail. The system of equations will then be presented as the remaining layers extrapolate the mentioned cases.

The heat balance in layer one of the FPC can be expressed in eq.1 and Fig. 3 as the glass layer is opaque to infrared radiation, the transferred heat transfer radiation through the glass is dropped from the equation.

$$\dot{q}_{conv,1}^{ext} + \dot{q}_{rad,1}^{(t) ext} + \dot{q}_{rad,1}^{(s) ext} + \dot{q}_{trans,c1}^{(s)} = \dot{q}_{cond,c1}$$
(eq. 1)

To obtain the equations to solve the system, the terms are resolved to compute the temperature of the surface 1. See eq. 2.

$$T_{c1}^{ext} = \frac{-\dot{q}_{rad,c1}^{(t)ext} - \dot{q}_{rad,c1}^{(s)ext} - \dot{q}_{trans,c1}^{(s)} + h_{c1}^{ext} T_{a} + \frac{k_{c1}}{e_{c1}} T_{c1}^{int}}{h_{c1}^{ext} + \frac{k_{c1}}{e_{c1}}}$$
(eq. 2)
$$\frac{\dot{q}_{cnt}^{ext} + \frac{k_{c1}}{e_{c1}}}{\int_{c1}^{ext} - \dot{q}_{trans,c1}^{(s)ext} + \dot{q}_{trans,c1}^{(s)ext}} + \dot{q}_{trans,c1}^{(s)ext} + \dot{q}_{trans,c1}^{$$

Fig. 3: Heat balance in layer 1

For layers 2 and 3, convection can be dropped from the equation since the convection inside the honeycomb layer is negligible and assumed as pure conduction (Fig. 4). Regarding the conductivity in the honeycomb, it can be computed as eq.3. The conductivity is a combination of air and honeycomb, and WF represents the honeycomb's wall fraction with respect to the air, as in Platzer (1992). In the study, the WF has been chosen as 0.011 since the honeycomb represents a small surface area of the overall plane surface of the FPC.

$$k_{TIM,eq} = WF k_{TIM} + (1 - WF) k_{air}$$
(eq. 3)

The balance in layers 2 and 3 can be computed as equations 4 and 5.

$$\dot{q}_{rad,2}^{(t) \text{ int}} + \dot{q}_{rad,2}^{(s) \text{ int}} + \dot{q}_{cond,c1} = \dot{q}_{trans,c1}^{(s)}$$
(eq. 4)
$$\dot{q}_{rad,3}^{(t) \text{ ext}} + \dot{q}_{rad,3}^{(s) \text{ ext}} + \dot{q}_{trans,TIM}^{(t)} + \dot{q}_{trans,TIM}^{(s)} = \dot{q}_{cond,TIM}$$
(eq. 5)

To solve these equations, it is relevant to note that T_{c1}^{int} should be equal to T_{TIM}^{ext} and that $\dot{q}_{rad,2}^{(t) int}$ is equal to $-\dot{q}_{rad,3}^{(s) ext}$ and similarly, $\dot{q}_{rad,2}^{(s) int}$ is equal to $-\dot{q}_{rad,3}^{(s) ext}$. Therefore, eqs. 4 and 5 can be combined to determine the

temperature in both layers, as seen in eq. 6.



Fig. 4: Heat balance in layer 2

Following the same procedure for all the surfaces and leaving the temperatures in the function of the external temperature variables, the following system of equations can be found:

$$T_{c1}^{ext} = \frac{-\dot{q}_{rad,c1}^{(t)ext} - \dot{q}_{rad,c1}^{(s)ext} - \dot{q}_{trans,c1}^{(s)} + h_{c1}^{ext} T_a + \frac{k_{c1}}{e_{c1}} T_{TIM}^{ext}}{h_{c1}^{ext} + \frac{k_{c1}}{e_{c1}}}$$
(eq. 7)

$$T_{TIM}^{ext} = T_{c1}^{int} = \frac{\dot{q}_{trans,c1}^{(s)} - \dot{q}_{trans,TIM}^{(s)} - \dot{q}_{trans,TIM}^{(s)} + \frac{k_{c1}}{e_{c1}} T_{c1}^{ext} + \frac{k_{TIM,eq}}{e_{TIM}} T_{c2}^{ext}}{\frac{k_{c1}}{e_{c1}} + \frac{k_{TIM,eq}}{e_{TIM}}}$$
(eq. 8)

$$T_{c2}^{ext} = T_{TIM}^{int} = \frac{\dot{q}_{trans,TIM}^{(s)} + \dot{q}_{trans,TIM}^{(t)} - \dot{q}_{trans,c2}^{(s)} + \frac{k_{c2}}{e_{c2}} T_{sil}^{ext} + \frac{k_{TIM,eq}}{e_{TIM}} T_{TIM}^{ext}}{\frac{k_{c2}}{e_{c2}} + \frac{k_{TIM,eq}}{e_{TIM}}}$$
(eq. 9)
$$T_{sil}^{ext} = T_{c2}^{int} = \frac{\dot{q}_{trans,c2}^{(s)} - \dot{q}_{trans,sil}^{(s)} - \dot{q}_{trans,sil}^{(t)} + \frac{k_{c2}}{e_{c2}} T_{c1}^{ext} + \frac{k_{sil}}{e_{sil}} T_{abs}^{ext}}{\frac{k_{c2}}{e_{c2}} + \frac{k_{sil}}{e_{sil}}}$$
(eq. 10)

To complete the heat balances, it is necessary to compute the temperature in the absorber. Thus, it is followed the same approach as in section 2.4. Absorber in Kessentini et al. (2014). The fin efficiency method is used to discretize each tube slice, as depicted in Fig. 5. Please notice that this is not a 2D discretization but a fin efficiency computation for each tube slice.



Fig. 5: Schematic representation of the control volumes at the fin and tube element of the absorber

The fin temperatures and the fluid temperatures are computed following eq. 11 and eq. 12.

$$\begin{split} T_{fin}^{i,j} &= T_a + \frac{s}{u_L} + \left(T_{bo} - T_a - \frac{s}{u_L} \right) \frac{\cosh(my_j)}{\cosh\left(\frac{m(W-D_0)}{2}\right)} \\ T_f^i &= T_a + \frac{s}{u_L} + \left(T_{fi} - T_a - \frac{s}{u_L} \right) e^{-(U_L n_t F' W x_i)/(inc_p)} \end{split}$$
(eq. 11)

The absorber temperature (T_{abs}^{ext}) can be computed as the mean temperature of the fins. Additionally, to calculate the overall heat transfer of the FPC, eq. 13 has been used.

$$U_{L} = U_{top} + U_{back} + U_{edge} = \frac{1}{R_{c1} + R_{TIM} + R_{c2} + R_{sil}} + \frac{1}{R_{ins} + R_{air\,gap}} + \frac{k_{ins}}{e_{ins}} \frac{P_{c}}{A_{c}}$$
(eq. 13)

In which R are the resistances produced by the several layers and P_c represent the perimeter and A_c represent the front area of the FPC. Iterating the system of equations, the temperatures in the layers can be computed and the efficiency estimated.

2.2. Radiation flux in the visible spectrum

The radiosities method is implemented to determine the radiative heat fluxes in the FPC. This method requires the computation of the view factors before the heat balances can be defined. However, in the proposed geometry, the calculation of the view factors can be solved easily with the assumption that if the layers are very close to each other, all the irradiance from one layer will impact the contiguous layer. Thus, the view factor of one layer to the other can be considered as eq. 14. The sum of the view factors should be equal to one. Therefore, the view factor of the ith layer to the contiguous layer (ith+1) needs to be equal to one. This simplified geometry reduces complexity in the radiosities equations.

$$F_{i,i} = 0; F_{i,i} + F_{i,i+1} = 1; F_{i,i+1} = 1$$
 (eq. 14)

To compute the radiosities (j) and the irradiations (g) is straightforward as the view factor simplifies the definition of the irradiations. For surface 1, eq.15 and eq 16 and the net heat transfer by radiation can be expressed as eq. 17. Fig. 6 represents the key variables and their position that interacted and were vital for this calculation.



Fig. 6: Radiosities method in the glass layer for visible irradiance

$j_{c1}^{(s)ext} = \rho_{c1}^{(s)} \dot{g}_{c1}^{(s)ext} + \tau_{c1}^{(s)} \dot{g}_{c1}^{(s)int}$	(eq. 15)
$\dot{g}_{c1}^{(s)ext} = F_{11}j_{c1}^{(s)ext} + F_{1s}j_s$	(eq. 16)
$\dot{q}_{rad,1}^{(s)ext} = j_{c1}^{(s)ext} - \dot{g}_{c1}^{(s)ext}$	(eq. 17)

Finally, the transmitted heat transfer through the layer can be defined as eq.18. This heat will be used in eq. 7 and eq. 8 as an input parameter.

$$\dot{q}_{trans,c1}^{(s)} = \tau_{c1}^{(s)} \left(\dot{g}_{c1}^{(s)ext} - \dot{g}_{c1}^{(s)int} \right)$$
(eq. 18)

Extrapolating this procedure for all the layers, a system of equations can be prepared depending on the radiosities.

$$j_{c1}^{(s)ext} = \rho_{c1}^{(s)} \dot{g}_{c1}^{(s)ext} + \tau_{c1}^{(s)} \dot{g}_{c1}^{(s)int} = \rho_{c1}^{(s)} I_{T} + \tau_{c1}^{(s)} j_{TIM}^{(s)ext}$$
(eq. 19)

$$j_{c1}^{(s)int} = \rho_{c1}^{(s)} \dot{g}_{c1}^{(s)int} + \tau_{c1}^{(s)} \dot{g}_{c1}^{(s)ext} = \rho_{c1}^{(s)} j_{TIM}^{(s)ext} + \tau_{c1}^{(s)} I_T$$
(eq. 20)

$$j_{\text{TIM}}^{(s)\text{ext}} = \rho_{\text{TIM}}^{(s)} \dot{g}_{\text{TIM}}^{(s)\text{ext}} + \tau_{\text{TIM}}^{(s)} \dot{g}_{\text{TIM}}^{(s)\text{int}} = \rho_{\text{TIM}}^{(s)} j_{c1}^{(s)\text{int}} + \tau_{\text{TIM}}^{(s)} j_{c2}^{(s)\text{ext}}$$
(eq. 21)

$$j_{\text{TIM}}^{(s)\text{Int}} = \rho_{\text{TIM}}^{(s)} \dot{g}_{\text{TIM}}^{(s)\text{Int}} + \tau_{\text{TIM}}^{(s)} \dot{g}_{\text{TIM}}^{(s)\text{ext}} = \rho_{\text{TIM}}^{(s)} j_{c2}^{(s)\text{ext}} + \tau_{\text{TIM}}^{(s)} j_{c1}^{(s)\text{Int}}$$
(eq. 22)

$$\mathbf{j}_{c2}^{(s)ext} = \rho_{c2}^{(s)} \dot{\mathbf{g}}_{c2}^{(s)ext} + \tau_{c2}^{(s)} \dot{\mathbf{g}}_{c2}^{(s)int} = \rho_{c2}^{(s)} \mathbf{j}_{TIM}^{(s)int} + \tau_{c2}^{(s)} \mathbf{j}_{sil}^{(s)ext}$$
(eq. 23)

$$j_{c2}^{(s)int} = \rho_{c2}^{(s)} \dot{g}_{c2}^{(s)int} + \tau_{c2}^{(s)} \dot{g}_{c2}^{(s)ext} = \rho_{c2}^{(s)} j_{sil}^{(s)ext} + \tau_{c2}^{(s)} j_{TIM}^{(s)int}$$
(eq. 24)

$$j_{sil}^{(s)ext} = \rho_{sil}^{(s)} \dot{g}_{sil}^{(s)ext} + \tau_{sil}^{(s)} \dot{g}_{sil}^{(s)int} = \rho_{sil}^{(s)} j_{c2}^{(s)int} + \tau_{sil}^{(s)} j_{abs}^{(s)ext}$$
(eq. 25)

$$j_{sil}^{(s)int} = \rho_{sil}^{(s)} \dot{g}_{sil}^{(s)int} + \tau_{sil}^{(s)} \dot{g}_{sil}^{(s)ext} = \rho_{sil}^{(s)} j_{abs}^{(s)ext} + \tau_{sil}^{(s)} j_{c2}^{(s)int}$$
(eq. 26)

$$j_{abs}^{(s)ext} = \rho_{abs}^{(s)} \dot{g}_{abs}^{(s)ext} = \rho_{abs}^{(s)} j_{sil}^{(s)int}$$
(eq. 27)

Finally, the heat transferred through the layers can be computed as:

$$\dot{q}_{trans,c1}^{(s)} = \tau_{c1}^{(s)} \left(\dot{g}_{c1}^{(s)ext} - \dot{g}_{c1}^{(s)int} \right) = \tau_{c1}^{(s)} \left(I_T - j_{TIM}^{(s)ext} \right)$$
(eq. 28)

$$\dot{q}_{trans,TIM}^{(s)} = \tau_{TIM}^{(s)} \left(\dot{g}_{c1}^{(s)ext} - \dot{g}_{c1}^{(s)int} \right) = \tau_{TIM}^{(s)} \left(j_{c1}^{(s)int} - j_{c2}^{(s)ext} \right)$$
(eq. 29)

$$\dot{q}_{trans,c2}^{(s)} = \tau_{c2}^{(s)} \left(\dot{g}_{c1}^{(s)ext} - \dot{g}_{c1}^{(s)int} \right) = \tau_{c2}^{(s)} \left(j_{TIM}^{(s)int} - j_{sil}^{(s)ext} \right)$$
(eq. 30)

$$\dot{q}_{trans,sil}^{(s)} = \tau_{sil}^{(s)} (\dot{g}_{c1}^{(s)ext} - \dot{g}_{c1}^{(s)int}) = \tau_{sil}^{(s)} (j_{c2}^{(s)int} - j_{abs}^{(s)ext}) = S$$
(eq. 31)

This system of equations will be used as input to solve the equations defined in 2.1.

2.3. Radiation flux in the infrared spectrum

As done in the previous section, the radiosities method is applied to compute the infrared radiation. The view factors can be calculated similarly as in section 2.2. However, implementing the radiosities (j) and the irradiations (g) is not as simple as explained in section 2.2. The surfaces can emit in the infrared spectrum and need to be considered for the calculation. For surface 1, eq.32 and eq 33 and the net heat transfer by radiation can be expressed as eq. 34. In contrast with 2.2., the sky temperature (T_c) needs to be considered instead of the heat flux coming from the sun. It is assumed that the glass is opaque to the infrared irradiance, and consequently, the transmissivity is equal to zero. This won't be the case for the honeycomb and the silica layers. Fig. 7 represents the key variables and their position that interacted and were relevant for this calculation.

$$\begin{split} j_{c1}^{(t)ext} &= \epsilon_{c1}^{(t)} \sigma T_{c1}^{ext^4} + \rho_{c1}^{(t)} \dot{g}_{c1}^{(s)ext} + \tau_{c1}^{(t)} \dot{g}_{c1}^{(t)int} = \epsilon_{c1}^{(t)} \sigma T_{c1}^{ext^4} + \rho_{c1}^{(t)} g_{c1}^{(s)ext} \qquad (eq. \ 32) \\ g_{c1}^{(t)ext} &= F_{11} j_{c1}^{(t)ext} + F_{1c} j_c = j_c = \sigma T_c^{\ 4} \qquad (eq. \ 33) \\ \dot{q}_{rad,1}^{(t)ext} &= j_{c1}^{(t)ext} - g_{c1}^{(t)ext} \qquad (eq. \ 34) \end{split}$$

The transmitted heat transfer is zero in this layer, but it will be expressed as if it was not, as an example. It is defined in eq. 35.

$$\dot{q}_{trans,c1}^{(t)} = \tau_{c1}^{(t)} \left(\dot{g}_{c1}^{(t)ext} - \dot{g}_{c1}^{(t)int} \right) = 0$$
(eq. 35)

Extrapolating this procedure for all the layers, a system of equations can be prepared depending on the radiosities.

$$j_{c1}^{(t)ext} = \varepsilon_{c1}^{(t)} \sigma T_{c1}^{ext^4} + \rho_{c1}^{(t)} \sigma T_{C}^{\ 4}$$
(eq. 36)
$$j_{c1}^{(t)int} = \varepsilon_{c1}^{(t)} \sigma T_{c1}^{int^4} + \rho_{c1}^{(t)} j_{TIM}^{(t)ext}$$
(eq. 37)

$$j_{\text{TIM}}^{(t)\text{ext}} = \epsilon_{\text{TIM}}^{(t)} \sigma T_{\text{TIM}}^{\text{ext}\,4} + \rho_{\text{TIM}}^{(t)} j_{c1}^{(t)\text{int}} + \tau_{\text{TIM}}^{(s)} j_{c2}^{(s)\text{ext}}$$
(eq. 38)

$$j_{\text{TIM}}^{(t)\text{int}} = \varepsilon_{\text{TIM}}^{(t)} \sigma T_{\text{TIM}}^{\text{int} 4} + \rho_{\text{TIM}}^{(s)} j_{c2}^{(s)\text{ext}} + \tau_{\text{TIM}}^{(s)} j_{c1}^{(s)\text{int}}$$
(eq. 39)

$$j_{c2}^{(t)ext} = \varepsilon_{c2}^{(t)} \sigma T_{c2}^{ext^{+}} + \rho_{c2}^{(s)} j_{TIM}^{(s)int}$$
(eq. 40)

$$j_{c2}^{(t)int} = \varepsilon_{c2}^{(t)} \sigma T_{c2}^{int^4} + \rho_{c2}^{(s)} j_{sil}^{(s)ext}$$
(eq. 41)

$$j_{sil}^{(t)ext} = \epsilon_{sil}^{(t)} \sigma T_{sil}^{ext^4} + \rho_{sil}^{(s)} j_{c2}^{(s)int} + \tau_{sil}^{(s)} j_{abs}^{(s)ext}$$
(eq. 42)

$$j_{sil}^{(t)int} = \epsilon_{sil}^{(t)} \sigma T_{sil}^{int^4} + \rho_{sil}^{(s)} j_{abs}^{(s)ext} + \tau_{sil}^{(s)} j_{c2}^{(s)int}$$
(eq. 43)

$$j_{abs}^{(t)ext} = \epsilon_{abs}^{(t)} \sigma T_{abs}^{ext^4} + \rho_{abs}^{(s)} j_{sil}^{(s)int}$$
(eq. 44)



Fig. 7: Radiosities method in the glass layer for infrared irradiance

Finally, the heat transferred through the layers can be computed as:

$$\dot{q}_{trans,c1}^{(t)} = \tau_{c1}^{(t)} \left(\dot{g}_{c1}^{(t)ext} - \dot{g}_{c1}^{(t)int} \right) = 0$$
 (eq. 45)

$$\dot{q}_{trans,TIM}^{(t)} = \tau_{TIM}^{(t)} (\dot{g}_{c1}^{(t)ext} - \dot{g}_{c1}^{(t)int}) = \tau_{TIM}^{(t)} (j_{c1}^{(t)int} - j_{c2}^{(t)ext})$$
(eq. 46)

$$\dot{q}_{trans,c2}^{(t)} = \tau_{c2}^{(s)} \left(\dot{g}_{c1}^{(t)ext} - \dot{g}_{c1}^{(t)int} \right) = 0$$
(eq. 47)

$$\dot{q}_{trans,sil}^{(t)} = \tau_{sil}^{(t)} (\dot{g}_{c1}^{(t)ext} - \dot{g}_{c1}^{(t)int}) = \tau_{sil}^{(t)} (j_{c2}^{(t)int} - j_{abs}^{(t)ext})$$
(eq. 48)

This system of equations will be iterated in parallel with the equations defined in 2.1 since it depends on the temperatures. The output of equations 45 to 48 will also serve as an input to the system of equations 2.1.

2.4. Remarks of the mathematical model

The numerical method proposed can be computed in a parallel object-oriented way because it needs several iterations to converge. Since some equations are quadratic, a relaxation factor of 0.9 is used to improve convergence.

Additionally, the optical and thermal properties considered in the present document will not be discussed in great detail. In the concrete case of the silica properties, they are not straightforward to estimate and require their proper discussion. As a generical introduction to the silica layer, it is necessary to emphasize that its thermal conductivity is affected by temperature (Fig. 8), and its transmissivity in the infrared spectrum needs to be estimated. Moreover, the conductivity provided by manufacturers should be reformulated to incorporate the radiosities method with the silica layer. The difference between the apparent conductivity in Fig. 8 and the thermal conductivity as used in the equation previously described consists of the apparent conductivity considering the optical properties in the infrared spectrum of the silica layer in an implicit way. This component should be extracted from the apparent conductivity and computed separately to compute radiosities.





Regarding the honeycomb layer, the transmissivity in the visible spectrum requires computing both the direct and the diffuse solar irradiance independently (the transmissivity of the honeycomb is lower for the diffuse irradiance), which makes the computation depends on the weather conditions. The direct transmissivity of the honeycomb is estimated in a conservative way to be 0,9 and the diffuse irradiance transmissivity close to 0,87. The diffuse ratio has been estimated to be of the 36% as it has been the average during the experimental period.

Nevertheless, glass and absorber optical properties can be defined as per the manufacturer's data without increased complexity.

3. Experimental data vs. numerical method

The experimental collector was manufactured according to the simulation's mathematical results and to prove the mathematical model.

3.1. Experimental setup

An experimental test bench is used to obtain the steady-state efficiency of the collector (see Fig. 9.). All the experimental data was registered and averaged by 15-minute periods on maximum irradiance conditions (incidence angle of 0°). The FPC was tested under different inlet temperature conditions to obtain the efficiency curve. The steady efficiency curve of the FPC has been obtained according to ISO 9806-1:1994 in the CTTC SOLAR CELL in Terrassa, Barcelona, Spain.



Fig. 9: Test bench used for the thermal characterization of the solar collectors

3.2. Experimental results of the first FPC

The 1st FPC manufactured was optimized using a preliminary numerical method. After running several simulations with that mathematical model, a silica layer of 2 cm was selected. In contrast, the best option for the honeycomb was the 7.5 cm thickness. It is the maximum available thickness in the market and reduces the silica needed to achieve high efficiencies. The other materials' thicknesses were set by manufacturing constraints or were decided to be studied layer on the project.

The glasses used were high transmittance and low emissivity, with a transmittance of 0.92 in the visible spectrum.

A 1st test campaign has been performed to validate the steady-state efficiency obtained by the preliminary numerical model. That model has resulted in overestimating the insulating capacity of the materials used and the optical efficiency of the manufactured FPC, as depicted in Fig 10. Nevertheless, part of the discrepancies observed between experimental and computed data is the manufacturing limitations discussed later.

The implementation of granular silica aerogel in the FPC has improved the first and second-order coefficients while deteriorating the optic efficiency of the FPC compared with previous studies of Kessentini et al. (2014). This behavior, yet expected, due to the implementation on a second glass layer and the silica, was more severe than predicted.

A relevant side-effect was found after the manufacturing of the prototype. Since the silica aerogel is placed between two layers without casing, the silica particles tend to fall to the bottom of the collector when the collector is tilted. This reduces the insulating capacity at the top of the FPC because it leaves some absorber area exposed directly to the second glass layer. This problem will be tackled in future versions of the FPC and discussed in the conclusions.



Fig. 10: Preliminary model vs. experimental FPC with transparent insulation materials (honeycomb and silica aerogel).

An important design constrain is the honeycomb temperature limit. Kessentini et al. (2014) implement an overheating protection system placed behind the FPC to avoid this problem. This implementation is intended to be avoided by implementing the silica layer. Once optimizing the FPC, a complete stagnation test will be performed to prove the durability of the TIM layer without a protection system. It is expected that the inner temperatures of the collector were reduced significantly, with good redesign and silica layer stabilization, making this objective potentially achievable.

With all these factors considered, the model was refined following the method described in section 2. of this document and including some parameters to tune the equations to make them closer to the real experimentation constraints. The proposed model introduced a better characterization of the silica layer and considered the honeycomb properties better for the diffuse irradiance (more details in point 2.4).



Fig. 11: Proposed model vs. experimental FPC with transparent insulation materials (honeycomb and silica aerogel).

As can be seen in Fig. 11, the proposed model without tuning resulted in, as well, an overestimation of the efficiency of the FPC. However, decent estimation of the experimental data was obtained after adequately adjusting the relevant parameters.

The results show the importance of the parameters that have been tuned to achieve a better approximation of the efficiency of the flat plate collector. Those parameters were the following:

- Silica thickness
- Air-silica compactness ratio

To achieve the results in Fig. 11, the silica thickness was increased by 1cm with respect to the design consideration (2cm), getting a total silica thickness to 3cm. This parameter change is because the absorber plate tends to buckle due to the silica weight and thermal expansion. This was considered in the manufacturing procedure, but the material used in the back of the collector to prevent the deformation has not been enough to keep the absorber in place. As a side-effect, the silica layer has more volume to fill and tends to fall to the bottom of the FPC. To consider the phenomena in the mathematical model, the air-silica compactness ratio is modified to a value of 33%. This ratio can be understood as the volume occupied by air in the silica region. As per manufacturing constraints, there will always be some air in the silica region, and it will never be 0%. The only way to get to the 0% of air would be to use non-granular silica. Which will be discussed in section 5.

Next summer a 2^{nd} test campaign will be performed, taking advantage of the previous experience, and using the refined mathematical model for an optimization analysis with the aim of improving the design and prototyping of the 2^{nd} version of the solar collector.

4. Optimization and parametric study

To optimize the overall performance of the FPC, a parametric study has been conducted by changing three main parameters:

- i) The glass transmissivity from 0.92 to 0.96 produces a high optical efficiency increment. This increment can be done by changing the glass used compared to the previous FPC;
- Second, the air-silica compactness ratio is set at 15%. Meaningful learning obtained in the 1st FPC design is that a 0% ratio can never be obtained using granulate silica, so it is realistic to recognize a certain degree of air in the silica layer. A 15% seems achievable, improving the casing and preventing some absorber expansion.
- iii) Third, several different thicknesses of silica layer to see the impact in the optical efficiency and the first and second order coefficients. The results of the parametric study can be seen in Fig. 12. The results have been compared with the 1st FPC manufactured, a honeycomb collector with a 0.96 transmissivity glass, and the experimental Kessentini et al. (2014) honeycomb collector with 0,92 transmissivity glass.

As can be seen in Fig. 12, the optimal thickness of the silica layer is 1cm. An important conclusion can be obtained. It is better to surpass the 1cm of silica instead of getting less than that since the second order coefficient increases sharply when the silica layer gets closer to 0.5cm. Another remark is that increasing the silica layer above 2cm has more drawbacks than advantages. The optical efficiency gets severely punished and brings the whole efficiency down making useless the improvement in the first and second order coefficients.



Fig. 12: Optimization of the FPC with transparent insulation materials (honeycomb and silica aerogel) vs. previous versions.

The use of a 0.96 transmissivity glass seems to impact the optical efficiency significantly. It improves the overall efficiency of the FPC for all the thicknesses of the silica layer significantly.

In contrast with the FPC with a honeycomb layer but no silica, the proposed FPC surpasses its efficiency in the high-temperature-difference region as expected with a pretty low impact on the optical efficiency.

Regarding the protection capacity of the silica to the honeycomb layer, as shown in Fig. 13, it is less than optimum since temperatures, for a 1cm silica, get above 100°C for stagnation conditions at an ambient condition of 20°C.



Fig. 13: Honeycomb layer temperature vs. the thickness of the silica layer for stagnation conditions

With a silica layer of 3cm, the FPC efficiency is punished, the temperatures decrease significantly in the honeycomb layer, but still above 130°C. This issue is something to keep in mind for the next generation prototype because it may force implementing an overheating protection system or a heat evacuation system.

Yet these results are relevant, but uncertainty always needs to be tackled, and the manufacturing limitations can drive those efficiencies down. The best way to assess the effects is to test them experimentally.

5. Future research and direction

After analyzing the results seems that implementing a higher transmissivity glass should be mandatory to improve the performance while paying close attention to the manufacturing details to keep the air-silica compactness ratio as low as possible. Additionally, a silica layer between 1 and 1.5 cm should be targeted to achieve the best possible overall efficiency while it may not be enough to protect the honeycomb layer.

A more detailed overheating analysis should be conducted to assess the honeycomb layer temperatures appropriately and improve the durability of the solar collector.

The use of vacuum techniques to force the compactness of the overall glass-silica-absorber subgroup could be worth the study. Yet, it can make the overall mounting process both complex and expensive.

Finally, monolithic silica dies instead of granulate silica aerogel should improve the overall efficiency for two reasons. The first reason is that the air-silica compactness ratio will be 0%, and the second is because the double glass, placed between the honeycomb and the silica, would not be necessary. This material change should improve both the optical efficiency and the first and second-order coefficients. The only drawback of this design is that the monolithic silica aerogel significantly increases the costs.

6. Conclusions

A crucial factor to consider for the 2^{nd} prototype is to prevent the silica particles from falling by implementing a better manufacturing technique to increase the air-silica compactness ratio, improving insulation. However, the mounting may be more complex.

Moreover, implementing 0,96 transmissivity glass layers should be mandatory to boost performance since

implementing it is notorious.

Finally, in conclusion, the FPC will need a thicker silica aerogel layer or a more compact silica layer to prevent the implementation of an overheating protection system. However, the wider the silica, the lower the maximum temperature achieved in the honeycomb layer. This question will need to be appropriately assessed in the next generation of FPC since increasing too much the silica layer significantly reduces the overall efficiency.

7. Acknowledgments

The authors want to thank the CTTC department's support for permitting the use of the CTTC experimental facility. Special thanks to Jian for his technical support in manufacturing the FPC and his support during the experimental activities.

Sponsored by the SUDOKET - SOE2/P1/E0677 project under the Interreg-Sudoe program

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5		
Preferred name	Symbol	Unit
Heat flux	ġ	W m ⁻²
Temperature	\dot{T}	Κ
Thermal conductivity	k	W m ⁻¹ K ⁻¹
Wall fraction	WF	
Heat transfer coefficient	h	W m ⁻² K ⁻¹
Thermal conductivity	k	W m ⁻¹ K ⁻¹
Thickness	е	m
Overall heat loss coef.	U	W m ⁻² K ⁻¹
Absorbed solar energy by	S	W m ⁻²
abs. plate		
Resistance coef.	R	W m ⁻² K ⁻¹
Number of tubes	n_t	
Tubes spacing	Ŵ	m
Position length	х, у	m
Aperture Area of FPC	A_{c}	m^2
Perimeter of FPC	P_{C}	m ²
View factor	F	
Irradiation	ġ	W m ⁻²
Radiosity	i	W m ⁻²
Emittance	Ē	
Reflectance	0	
Efficiency	n	
Solar irradiance on FPC	Ġ	W m ⁻²

Table 1: Symbols for properties

Appendix: Units and Symbols

Table 2: Suffixes for properties

SuffixesSymbolRadiative heatradConvective heatconvConductive heatcondTransmitted heattransVisible spectrumsInfrared spectrumtCover glassc1HoneycombTIMInterior glassc2Silica aerogelsil
Radiative heatradConvective heatconvConductive heatcondTransmitted heattransVisible spectrumsInfrared spectrumtCover glassc1HoneycombTIMInterior glassc2Silica aerogelsil
Convective heatconvConductive heatcondTransmitted heattransVisible spectrumsInfrared spectrumtCover glassc1HoneycombTIMInterior glassc2Silica aerogelsil
Conductive heatcondTransmitted heattransVisible spectrumsInfrared spectrumtCover glassc1HoneycombTIMInterior glassc2Silica aerogelsil
Transmitted heattransVisible spectrumsInfrared spectrumtCover glassc1HoneycombTIMInterior glassc2Silica aerogelsil
Visible spectrumsInfrared spectrumtCover glassc1HoneycombTIMInterior glassc2Silica aerogelsil
Infrared spectrumtCover glassc1HoneycombTIMInterior glassc2Silica aerogelsil
Cover glassc1HoneycombTIMInterior glassc2Silica aerogelsil
HoneycombTIMInterior glassc2Silica aerogelsil
Interior glassc2Silica aerogelsil
Silica aerogel sil
Absorber abs
Vector perpendicular to ext
collector plane and
pointing up
Vector perpendicular to int
collector plane and
pointing down
Ambient a
Positional index or inlet i
Outlet o
Fin fin

Best practices for PVT technology

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Abstract

The PVT technology combines solar PV and solar thermal in the same PVT panel. In this way, both electricity and heat are produced by the PVT panel. Compared to the PV technology and the solar heating technology the PVT technology is in the early market stage with only few small and weak industries active.

Best practices for the PVT technology, which is still under rapid development, are summarized. Marketed systems with different PVT panel types, different PVT system types with different components for different applications are considered. The potential advantages for PVT systems and the needs for key actors in order to establish a successful sustainable future PVT market are given.

Finally, recommendations for a subsidy scheme for PVT systems are given, so that a PVT market can be developed in parallel with the successful PV market.

Keywords: PVT panels, PVT systems, applications, best practices

1. Introduction

Within the project PowerUp MyHouse partners from Turkey, Portugal, Sweden, Lithuania and Denmark cooperate on preparation of teaching materials on PVT systems. A part of the work has focus on best practices for the PVT technology. This paper summarizes the findings, with inputs from all participants.

The PVT technology combines solar PV and solar thermal in the same PVT panel. The panel consist both of PV cells and an absorber in good thermal contact with the PV cells. PVT panels can provide electricity, heating and cooling. The PVT technology offers a number of potential advantages: The efficiency of the PV part can be somewhat increased by cooling the PV panel by air or fluid circulation through the absorber. Compared to separate PV panels and solar collectors, materials for the panels can be saved by using PVT panels. Further, roof and façade areas are utilized in a better way with PVT panels than with separate PV panels and solar collectors. Additional, by integrating PVT modules into building roofs and facades, the use of building materials, can be reduced.

Further, the PVT panel encapsulation technology is the same as for PV panels. Consequently, since PVT panels during operation have a lower temperature than similar PV panels, the lifetime of PVT panels is expected to be higher than the lifetime of PV panels.

The PVT economy is still today difficult to calculate precisely, based on market prices and existing installations, as it is an early market where costs always are much higher than in a mass market. The potential economic advantages are though large, compared to separate PV or solar heating systems, as the same mounting structure, installation work and almost the same module design are used.

There are also disadvantages for PVT system: It is still a new technology and for many applications the optimal designs of the PVT systems have not been elucidated. PVT panels are relatively expensive, since the panels are not mass produced. International standards for PVT panels and PVT systems are still not available. It is much more complicated, time consuming and expensive to test PVT panels than to test PV panels (normally only an instantaneous peak power flash test is used). The system designs are often relatively complicated making installation time consuming and complicated. Installers do not promote systems, which are difficult to install. PVT installer training is therefore very important. The technology is still by many key actors considered unproven.

The PVT market is still in the early stage. By the end of 2020, 1,275,431 m² PVT systems were in operation worldwide. During the last years from 2017 to 2020 an average yearly growth rate of the market of about 9% was observed, Weiss and Spörk-Dür (2021). Approximately half of the PVT area consist of air cooled PVT panels. The heated air is often used to heat the same buildings, where the PVT panels are in operation. The other half of the PVT systems are based on PVT panels with absorbers, where a solar collector fluid cools down the PV cells while circulated through the absorber.

2. PVT panels

Different PVT panel types are available. Figure 1 shows a typical flat plate PVT panel, a low concentrating LCPVT panel and a PVT panel cooled by air. The PVT panels can be uncovered or covered, equipped with a cover plate, typically a glass cover. Further, PVT solar collectors are either classified as liquid or air PVT's, characterized by its heat transfer fluid. Typical liquids are water or glycol/water mixtures.



Fig. 1: Typical PVT panels, Perers et al. (2021).

Concentrating (CPVT) panels utilize small solar cell areas and normally produce high temperatures. The electrical efficiency of the solar cells is therefore low, due to the reduced PV cell efficiency, at increased cell temperature. However, based on the aperture or gross area of the panel, the electrical efficiencies of the PVT panels are high. Moreover, concentrating PVT collectors can be labelled by its concentration ratio in three different categories, such as with low, medium and high concentration factors. Typically, low concentration PVT collectors are used as a part of a stationary (fixed collector tilt angle) solar energy systems, while high concentration PVT collectors require a one-axis or two-axis tracking system.

PVT panels with cover plates produce higher temperatures than uncovered PVT panels. Consequently, the electrical efficiency of the covered PVT panels is lower than the electrical efficiency of the uncovered PVT panels.

In most cases, PVT air collectors have high heat losses compared to liquid based PVT panels and they are therefore less sensitive to overheating. Consequently, air PVT panels have relative high electrical efficiencies.

PVT liquid collectors are more complicated to install than air cooled PVT collectors, while the air handling system inside the house normally needs more space and materials

In most PVT panels monocrystalline PV cells are used due to their enhanced electrical efficiency and higher solar absorption compared to polycrystalline PV cells. Thin-film solar cell technologies (e.g. CIGS and CdTe), are typically characterized by their lower temperature coefficient, which makes them very attractive for PVT panels with high temperatures. In high concentrating PVT applications, multi-junction PV solar cells are typically used.

The electrical performance of a PVT panel is measured and given as an instantaneous peak power at a solar irradiance of 1000 W/m² and an ambient and PV cell temperature of 25°C. The electrical efficiency of a PVT panel is given as the ratio between the peak power and (PVT area x 1000 W/m²).

The reduction of the electrical efficiency of a PVT panel with increasing PV cell temperature is given by equation 1, which represents the traditional linear expression for the PV electrical efficiency η_{el} .

(eq. 1)

$$\eta_{el} = \eta_{0,el} \left(1 - \beta (T_c - T_{ref}) \right)$$

where

Tc is PV cell temperature, °C

Tref is reference temperature equal to 25°C, °C

 β is the coefficient of temperature, °C⁻¹

η0,el is the electrical efficiency of the PVT panel at a temperature of 25°C, -

The thermal efficiency of a PVT panel can often in a simplified way be given by equation 2.

$$\eta = \eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \frac{(T_m - T_a)^2}{G}$$
(eq. 2)

where

 η is the thermal efficiency of the PVT panel, -

 η_0 is the peak thermal efficiency of the PVT panel, -

a1 is the heat loss coefficient of the PVT panel at ambient temperature, W/(m²K)

a2 is temperature dependence of heat loss coefficient of the PVT panel, W/(m²K²)

T_m is the mean solar collector fluid temperature in the PVT panel, °C

T_a is the ambient air temperature, °C

G is the solar irradiance on the PVT panel, W/m²

PVT panel efficiencies are determined by tests at test institutes. In order to evaluate the current state of commercially available PVT panels and their electrical and thermal performance, seven different PVT collectors (Solarus, Abora, Dual Sun, Solimpeks, EndeF, Fototherm and Solator) are selected and compared in Table 1. Figure 2 shows electrical efficiency of the PVT products at a reference temperature of 25°C. Figure 3 shows the thermal efficiency of the PVT products at a total solar irradiance on the PVT panels of 800 W/m² as a function of the difference between the mean solar collector fluid temperature of the PVT panel and the ambient air temperature. The thermal efficiency is measured with the PV part active, otherwise too high parameter values are derived from the test.

Company	D INC II			Size [m ²] P Price			PV Specifications		Thermal Specifications			
	Panel Model	I echnology	Country	Gross Aper	Aperture	gross]	Cell Type	Power Peak [W]	Eff. [%]	ηο	a1 [W/m².k]	a2 [W/m².k²] 0.014 0 0 0 0.067 0.021
Solarus	Power Collector	C-PVT- Glazed	Netherlan ds	2.57	2.31	253	Mono	270	10	0.47	3.78	0.014
Abora	aH72	PVT-Glazed- Water-airgap	Spain	1.96	1.88	204	Mono	350	17.8	0.7	5.98	0
Dual Sun	Wave - 280	PVT-Unglazed- Water-N/A	France	1.66	1.58	452	Mono	280	17.2	0.578	11.4	0
Solimpeks	Volter Powertherm	PVT-Glazed- Water-airgap	Turkey	1.43	1.42	243	Mono	180	16	0.486	4.028	0.067
EndeF	Ecomesh	PVT-Glazed- Water-airgap	Spain	1.61	1.55	596	Mono	260	15.95	0.51	4.93	0.021
Fototherm	FT250Cs	PVT-Unglazed- Water-N/A	Italy	1.61	1.59	618	Mono	250	15.5	0.559	9.123	0
Solator	PVTHERMA U 300	PVT-Unglazed- Water-N/A	Austria	1.64	-	-	Mono	300	18.5	0.499	11.84	0

Tab. 1: Different PVT panels and their principal parameters, Perers et al. (2021)



Fig. 2: Electrical efficiency of PVT panels, Perers et al. (2021).



Fig. 3: Thermal efficiency of PVT panels, Perers et al. (2021).

From figures 2 and 3 it is seen that the electrical efficiencies of the marketed PVT panels vary between 10% and 16%, while the thermal efficiencies vary between 0% and 70%, strongly depending on the temperature level of the panel and the product in question.

3. Best practices for PVT systems

PVT systems can be used for many different applications and many different PVT system designs are possible. Figure 4 gives an overview of PVT panel technologies and PVT applications for different temperature levels.



Fig. 4: PVT technology and applications for different temperature levels, Lämmle et al. (2020).

Approximately half of the presently installed PVT area of all PVT systems in operation consist of air cooled PVT panels. PVT air collectors are suitable for buildings where air is used for heating, see figure 5. In these relatively simple systems, the air flow rate, plays a key role in lowering the solar cell temperature and increasing the overall energy efficiency of the system. The thermal efficiency of the panels is typically situated in the range from 20% to 40%.

The other half of the PVT systems in operation, are based on PVT panels with thermal absorbers, where a solar collector fluid cools down the PV cells while circulated through the absorber. The solar collector fluid can in simple PVT systems be used for heating swimming pools.

PVT panels can be combined with a heat pump, which can achieve a high efficiency by utilizing the heat produced by the PVT panel. Preferably on the cold side of the heat pump. In these systems simple uncovered PVT panels are often used and the systems inclusive one or more thermal storages plus electrical batteries, can be controlled in a smart way, optimizing the interplay with the electrical grid.





PVT systems with liquid based PVT panels can also be used to cover domestic hot water consumption and/or space heating demand. Lämmle, Oliva, Hermann, Kramer and Kramer (2017) suggested four different systems,

see the principle sketches in figure 6.



Fig. 6: System principles. (A) domestic hot water in a single-family house, system. (B) domestic hot water in a multi-family home. (C) combi system in a single family house. (D) solar heat pump system in series/regeneration configuration in a single-family house.

System (A) is a domestic hot water system in a single-family house. It is the classical system for solar collectors and is therefore considered a promising application with a potentially big market for PVT collectors. If the PVT system is not oversized compared to the load the operating temperatures can be quite low.

System (B) is a domestic hot water system in a multi-family house, MFH. The system is typically dimensioned in such a way that a relatively low solar fraction is reached. Therefore, the operating collector loop temperatures are relatively low.

System (C) is a combined domestic hot water and space heating system in a single-family house. It is a challenging application with high requirements for the thermal efficiency of the PVT collector, since the heat demand occurs mostly in winter, with low levels of solar radiation and low ambient temperatures. Here avoiding oversizing is very important. Floor heating, like in this example, gives lower operating temperatures for the PVT. Often also a heating demand exist in summer.

System (D) is a heat pump system in a single-family house, SFH. The PVT panel and the heat pump supply space heat and domestic hot water. A synergetic integration of PVT panels can be reached when the PVT panel is coupled to the heat pump, as cold side heat source, or for the regeneration of a ground heat exchanger, which potentially offers the lowest PVT collector temperatures.

The electrical system can also be coupled with an electrical power meter, power optimizers in each PVT panel, battery storage systems and smart controllers, optimizing the interplay with the electricity grid.

PVT systems can also be used for high temperature applications, for instance to cover process heat demands for industries. In such systems advanced concentrating tracking PVT panels can be used. However, these systems are not commonly used so far.

PVT panels can also be used for cooling, as the panel surfaces undercool below the ambient temperature during night up to 10 K, by radiation to a clear sky. This potential is not so much utilized yet but could be used for both air and liquid unglazed PVT panels.

On the cold side of a heat pump system, heat can be extracted also during night, from the PVT panels, especially in windy and cloudy periods.

4. Needs for key actors

The PVT market is small and PVT manufacturers and installers need to be supported in the coming years in order to further develop and utilize the potential of the technology. To secure a high quality of installed PVT systems, prefabricated and easy to install components, for PVT systems, must be developed by manufacturers. It is recommended to support manufacturers in their efforts to develop and demonstrate the reliability of such components, through national and international energy research projects.

Also development of suitable education materials on PVT systems, for installers, consultants and energy planners are needed. Dedicated easy to use design software, directly connected to test standard results, is also important. Further, to secure the quality and safety of the systems, requirements on well educated PVT system installers must be established. It is therefore recommended to establish requirements on certified PVT installers, so that only certified installers are allowed to install PVT systems.

It is also recommended to educate university students in the building and energy sectors on PVT systems, and to carry out information campaigns on the technology. In this way PVT systems will not be forgotten as a solution for future buildings.

In order to establish a sustainable PVT system market there are needs for improvements on all levels. The following needs can be mentioned:

General needs:

- Design Tools for PVT systems
- Decreased costs for PVT systems, compared to separate PV and solar heating systems
- Development of simple and easy to install PVT systems
- A complete test standard for PVT systems like for PV and solar heating systems
- Teaching on all levels, also architects and installers
- Demo systems with proven performance and reliability. "Bankability" = Banks/Investors rely on the technology, to lend money.
- Proven building integration designs

Needs for key actors:

Researchers:

- Development of standards for PVT panels
- Development of standards for PVT systems
- Development of planning/optimization tools for PVT systems

Manufacturers:

• Development of improved PVT system types

• Development of prefabricated components for PVT systems: PVT panels, heat pumps, storages etc.

Project planners, consultants, decision makers, energy planners:

- Education on PVT systems
- Different PVT demonstration systems in different locations followed up during many years with the aim to document high reliability, high performance and long life time of PVT systems

Installers:

• Installer education on PVT systems

PVT systems are on the market in competition with PV systems. In order to achieve a successful PVT market in the future, it is additional needed that governments are supporting the technology by means of subsidy schemes. A proposal for a subsidy scheme is given in the next section.

5. Recommendations for PVT subsidy scheme

Experience from earlier subsidy schemes has shown that it is important not to introduce sudden changes in the subsidy conditions for the whole life time of the schemes. Since the PV market, especially for large ground based PV systems, is booming for the moment, there will soon be a surplus of solar electricity produced in summer days in the electrical grids. Assuming that the subsidies for PVT systems are related to the electricity delivered to the grid, this might result in sudden and surprising changes of the future subsidy rules. This is especially unfortunate for PVT systems, still being in the early market stage. To give PVT systems a fair chance compared to PV systems, which are already in a mass production and mass market stage, a special high subsidy level for PVT systems is suggested for the next 10 years. It is estimated that this can create a sustainable market for PVT systems along with a sustainable market for PV systems.

The following principles for a subsidy scheme are suggested:

- The subsidy is only payed as long as the system is working and according to how high the energy production is, in Euro per kWh. This also promotes a sustainable aftermarket for repair and upgrade of systems.
- The subsidy level is lowered year by year for new customers, according to the system cost development on the market.
- Early PVT adaptors/investors get a contract with a high enough fixed subsidy in Euro per kWh, stable over 10 years, to create a more predictable payback time, even when the reduction of systems costs and subsidy reductions, are fast for later customers.
- The kWh meter is located directly after the PVT inverter, to avoid economic uncertainties, due to local differences in self-consumption.
- If possible, also a meter on the thermal side can be used with a different lower subsidy level.
- These meter results can also be used to assure and compare system performance figures and help companies to improve the systems. This is in line with the emerging IoT 5G information technology.

6. Conclusions

The PVT technology is a promising new technology offering solutions to cover electricity, heating and cooling demand of buildings.

Today the PVT market is small, and the companies in the field are small and weak. The PVT market is sensitive to rapid changes in rules and support schemes.

Consequently, in order to utilize the potential of the technology on the market, there is a need for long term stable support on all levels: Support for development of prefabricated components and systems, support for education of key actors in the field, information campaigns on the technology, requirements on certified PVT installers and a favorable subsidy scheme for PVT systems.

7. Acknowledgments

The authors are thankful for the support given by EU to the project PowerUp MyHouse, agreement number 2020-1-TR01-KA202-093467 within the programme Erasmus+ Strategic Partnerships for vocational education and training.

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Performance Assessment of Concentrated Photovoltaic Thermal (CPVT) Solar Collector at Different Locations

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Abstract

The double MaReCo (symmetric reflector geometry) solar collector (DM-CPVT) has been designed and developed by MG Sustainable Engineering AB (MG) and the University of Gävle (HiG). Performance and overall electrical and thermal parameters of the collector have been studied and presented. The outdoor tests have been performed in both Sweden during the summer months of 2020 and Greece in September of 2020. The goal of the studied designs is to optimize the incoming solar radiation that can be collected without the need for tracking. This is possible due to the use of a symmetric reflector geometry with low concentration factor and lower collector depth. The use of a symmetric reflector geometry allows higher annual outputs worldwide. Furthermore, a low concentration factor is necessary to avoid tracking and a lower collector depth to reduce the shading, which is particularly important for the electrical production of these DM-CPVT design concepts. The testing facilities in both locations are also described in this paper. The information on the thermal performance of a collector is important for the prediction of the energy output of any solar system. The thermal properties assessment of the DM-CPVT collector followed the procedures of the ISO 9806:2017 standard and reported. The outdoor testing results have been validated with a deviation of 2.8% and 2.4% for both thermal and electrical peak efficiencies between the testing facilities, respectively. Regarding the Incidence Angle Modifier testing results, the deviation is negligible for all angles of incidence, which shows that outdoor testing procedures can be fairly accurate when tracking systems are not available. Keywords: CPVT, DM-CPVT, Solar Collector Testing

1. Introduction

The active application of solar energy technologies relies mainly on the use of solar thermal (ST) systems for heat generation and photovoltaic (PV) systems for electricity generation. The low surface power and energy density of PV modules, combined with the relatively low exergy of the solar flat plate thermal collectors, and the limited available ground area can be overcome by higher combined electrical and thermal (per unit area) efficiencies of a solar photovoltaic-thermal (PVT) system (Dwivedi et al. 2020; Kenny et al. 2003). A PVT collector is able to generate electricity and heat from the same area and is a single unit formed by a combination of PV and solar thermal technologies (Gomes et al. 2014; Zhang et al. 2012). PVT collectors have several applications in residential and industry such as, solar drying, water desalination, water and space heating, solar cooling, building integrated skins façades, etc. (Charron and Athienitis 2006; Sultan and Efzan 2018).

In recent years, several studies on PVT have been published. (Aste et al. 2016) presents a mathematical model for energy simulation of PVT systems in three different locations. (Keizer et al., 2016) stated that the efficiency of a PVT system is significantly high when comparing with PV systems. (Proell et al. 2016) investigates the performance of the PV systems and reports that these systems only convert 10-20% of the incoming solar radiation in electricity. Part of the remaining absorbed radiation can be converted to heat by a PVT collector. Furthermore, PV temperatures can potentially be reduced, thereby increasing the electrical yield. PVT collectors improve thermal efficiency by concentrating sunlight with CPC reflectors, allowing for more solar thermal applications. (Lämmle et al. 2017) findings show that the highest overall yields and the optimum energetic usage of the collector surface area are achieved by thermally optimized glazed PVT collectors with low-emissivity coatings. When compared to a side-by-side installation of flat plate collectors and PV modules with comparable thermal output, these collectors provide up to three times the electrical output. (Tomar, Tiwari, and Bhatti 2017) studies highlight that, improving the overall thermal efficiency of a PVT collector with the integration of an air duct behind the photovoltaic module enhances the overall thermal efficiency of the collector by extracting the excess heat released by the modules.

(Joshi and Dhoble 2018b) research reveals the concept of PVT systems is almost five decades old. But still, the technology is not much commercialized. (Maatallah, Zachariah, and Al-Amri 2019) reports that, from a financial standpoint and overall exergy basis, the payback period for the water-based PVT-PCM system is roughly 6 years, which is 11.26 % shorter than for traditional PV panels. In addition, when compared to traditional PV panels, the water-based PVT-PCM system has a long-term lifespan conversion efficiency of roughly 27%. (Guarracino et al. 2019) reports that the electrical and economic performance of PVT systems is highly dependent on various design and operational considerations such as materials and geometry. All these findings are showing how photovoltaic-thermal (PVT) solar collectors can achieve higher combined electrical and thermal (per unit area) efficiencies. The thermal coupling of PV cells with solar thermal absorbers enhances the thermal energy harvesting through a heat transfer cooling (HTF) fluid that not only cools down the PV cells below the operating temperature of standard PV modules but also improves electrical performance. The PVT thermal performance is often assessed using ISO 9806:2017 as the international standard for solar thermal collectors, and electrical performance is evaluated by IEC standards. Furthermore, PVT solar collectors can apply for Solar Keymark certification under particular rules, in which the thermal performance is measured using synchronous thermal and electrical generation under maximum power point conditions, as the heat and electricity influence each other (Jonas et al. 2019).

A heat transfer cooling fluid (normal water with a percentage of an anti-freeze fluid) is used in PVT systems to recover the excess thermal energy generated by the PV cells, hence increasing the electrical conversion efficiency of the collector (Helmers and Kramer 2013). PVT systems, on the other hand, are limited to work at low temperatures (30-80°C), making them appropriate for domestic hot water heating (DHW) (Miljkovic et al. 2011). PVT collectors can be categorized according to their specific operating temperature ranges, system layout, design (glazed, unglazed, and concentrating), and heat transfer medium (air and water, for commercial systems) (Zondag 2008). These systems can be based on concentration (e.g. Compound Parabolic Collector, CPC) or non-concentration configurations. For instance, for low concentration ratios and truncated optics, CPC is a reflector geometry that can concentrate a significant amount of solar radiation towards the receiver without necessarily requiring tracking. There is little research on Low Concentrating Photovoltaic-Thermal (LCPVT) available due to the difficulty of integrating concentrating systems with PV cells (Joshi and Dhoble 2018a). (Koronaki and Nitsas 2018) revealed one of the few situations in which the optical and electrical efficiencies are proven to be about 34% and 15%, respectively. Furthermore, the Incidence Angle Modifier (IAM) presented by them shows that this type of CPC is highly sensitive to specific incident angles. It should be considered that lowering the receiver area in concentrating stationary collectors causes reflection losses and a penalty in IAM. (Sharaf and Orhan 2015) studied PVT (CPVT) systems, and the goal was to combine concentrators with PV and thermal energy. This system is categorized into low, medium, or high concentration ratio technologies; also, it is possible to be stationary or be coupled with a tracking system. (Lämmle et al. 2016) investigated that combining the thermal and electrical systems into a single system optimizes the use of solar resources. By that, area dedicated to solar energy production could be decreased. However, this technology still has some challenges that need to be overcome before using it on a large and commercial scale. One of these challenges is partial shading which (Decker and Jahn 1997) have investigated. Furthermore, (Bunthof et al. 2016) showed that partial shadowing is the primary parameter for decreasing the energy yield of PV arrays. (Woyte, Belmans, and Nijs 2003) studied one possible solution to overcome this challenge by using bypass diodes which allow PV arrays to produce at a lower capacity. In this method, electrical current flows in a different path, and this causes a minor fraction of the total power. (Bunthof et al. 2016) conducted a study that shows costs of the solar collectors increased by adding bypass diodes to the PV arrays. Considering all these parameters, this study focuses on a PVT receiver without a bypass system.

(Cheng et al. 2010) studied fixed CPVT (either in one or two dimensions), and in this study, irradiation distribution on the receiver is considered to be uniform. It should be considered, most concentrating solar collectors mainly provide a non-uniform flux distribution and due to this problem, asymmetric heating patterns create hot spots on the PV cells. To predict the energy output of various solar thermal systems, information on the thermal performance of a wide scope of available solar collector technologies is of extreme importance. Several standards are available to assess the solar thermal collector efficiency, regardless of the technology. Two kinds of tests are possible: the steady or quasi steady-state test and the quasi-dynamic test. For liquid heating collectors, use as a base for their thermal output calculations both models presented in ISO 9806:2017. An electrical performance model based on the work developed by (Lämmle et al. 2017) is available.

2. Electrical and Thermal performance model

2.1 Electrical performance model

To calculate the electrical performance of DM-CPVT, a simplified electrical performance model based on the work developed by (Lämmle et al. 2017) has been employed. The model considers the instantaneous performance ratio (PR) due to incidence angle losses, being expressed by eq. 1 for θ greater than zero (Duffie and Beckman 2013).

$$PR_{IAM} = 1 - b_0 \cdot \left(\frac{1}{\cos \theta} - 1\right)$$
 eq. 1

Where b_0 is the constant for the incident angle modifier. Make it more understandable, the cell temperature $t_{cell, PVT}$ was replaced by the fluid mean temperature t_m due to lack of knowledge regarding the solar cell temperature behavior (in relation with the fluid temperature), thus the temperature dependence of the electrical efficiency is expressed by eq. 2 (Skoplaki and Palyvos 2009).

$$PR_{T} = 1 - \beta \cdot (t_{m} - t_{ref})$$
 eq. 2

Where t_{ref} is the reference temperature. Due to the selected concentration factor, the low irradiance behavior PR_G presented by (Heydenreich, Müller, and Reise 2008) was not considered, thus the instantaneous specific electrical power output P_{el} is given by the following eq. 3 (Lämmle et al. 2017).

$$P_{el} = \eta_{el,STC} \cdot PR_{IAM} \cdot PR_T \cdot G \qquad \text{eq. 3}$$

Where the temperature coefficient of electrical power β was set to 0.4%/K (Aste et al. 2016) and the standard panel efficiency η_{eLSTC} to 10%.

2.2. Thermal performance model

To estimate the constant parameters of the collector performance equation, the results have been analysed. The equation is shown in

$$\dot{Q} = A_G[\eta_0 G_{hem} - a_1(T_m - T_a) - a_2(T_m - T_a)^2 - \alpha_8(T_m - T_a)^4]$$
eq. 4

In this equation, \dot{Q} is the heat gain which is calculated by the test data, A_g is the gross area, $n_{0,hem}$ is the peak collector efficiency based on hemispherical irradiance G, on the collector surface, a1, a2, and a8 are the loss parameters (defined through this process), T_m is the mean collector temperature, and T_a is the ambient temperature.

In the above equation, the parameters a_2 and a_8 are very small and lower than three times the standard deviation and thus can be omitted. In eq. 4, regarding the order of each equation the specific heat gain is given, respectively, once the incident angle modifiers have been set to unity, which is valid for the collector at tracking mode.

$$\frac{Q}{A_g} = \eta_0 G_{hem} - U(T_m - T_a)$$
eq. 5

$$\frac{Q}{A_a} = \eta_0 G_{hem} - a_1 (T_m - T_a) - a_2 (T_m - T_a)^2$$
eq. 6

$$\frac{\tilde{Q}}{A_g} = \eta_0 G_{hem} - a_1 (T_m - T_a) - a_2 (T_m - T_a)^2 - a_8 (T_m - T_a)^4$$
eq. 7

According to the international standard ISO 9806:2017, a Steady-State testing procedure has been planned and done, which were further normalized to the gross area of the specific DM-CPVT.

3. CPVT Collector Design

DM-CPVT is a concentrating, hybrid solar photovoltaic and solar thermal collector (CPVT), which generates both electricity and heat from the same gross area. The collector reflects and concentrates the incoming sunlight, from its reflective mirrors to the bottom side of a (horizontally placed) PVT receiver. This reflector geometry is based on a MaReCo and CPC geometry that has been presented previously by (Cabral et al., 2019). For the DM reflector geometry, in this study, the receiver placement has been kept constant with a gap between the top of the receiver and the glass of 33 mm (Figure 1).



Figure 1. Cross-section view (with dimensions) of the general DM geometries. Circular sections A and B with 80 mm radius and an air gap of 33 mm. A (71° circular section); B (30° circular section); C (parabola section).

This gap has been implemented to reduce convection losses (Duffie and Beckman 2013). An additional gap of around 24 mm has been considered to evenly distribute the reflected sunlight on the bottom side of the receiver. The collector and reflector length were set to 2350 mm, to cope with the shadow created by the lack of reflector in the longitudinal direction. The geometry has an arc angle of around 101° (section A: 71° ; section B: 30°). The 30° arc angle employed in the circular section B, has the aim to compensate the Earths' declination ($\pm 23.45^{\circ}$) so that the collector has a wider range of working hours. Information on the main parameters for DM geometry design are presented in the following Table 1.

Table 1. Summary of the main parameters for DM geometry design concept.

Geometr y	Concentration factor (Ci)	Reflector depth (z) [mm]	Receiver dimensions (L/W/T) [mm]	Air gap ¹ [mm]	Gap² [mm]	Radius [mm]	Acceptanc e half- angle $(\theta_c) [^\circ]$	Circular section arc- angles [°]
DM-CPC	1.3	128	2310/165/14.5	33	24	80	23	101° (71°+30°)

To cope with the short spectral response of monocrystalline silicon solar cell, a reflector from Almeco (Solar Vega SP295f) with an electrical spectral reflectivity in the visible range of ρ = 95 % and a specular reflectance \geq 91 % has been selected. Furthermore, the total solar reflectance is 92 % with a length of around 2350 mm. The Solarus Sunpower bifacial PVT receiver has been used and has a receiver core with 2310 mm of length, a width of 165 mm and 14.5 mm of thickness. The cell string layout has a length of 2100 mm which comprises 38 one-third-size PV cells (to lower the amount of current in each cell) divided into 4 sub-strings (each one with one diode) of 8-11-11-8 PV cells. The PV cells are encapsulated in a silicone gel from Wacker-Elastosil Solar 2205 with a total thickness of 3.5 mm, with a reported thermal conductivity of 0.2 W/m.K and light transmittance of 97 %.

The PVT absorber has 8 elliptical channels to increase the heat transfer between the aluminum receiver core and the Heat transfer Fluid (HTF), increasing this way the HTF temperature and at the same time lowering the PV cell overall temperature, and thus enhancing the electrical efficiency. The electrical power output of PV modules can be improved by employing smaller sized silicon solar cells as it can effectively reduce the series resistance loss due to lower cell-to-module losses (Haedrich et al. 2014). The selected PV cells from Lightway Solar are characterized by an electrical efficiency of 20.1 %, theoretical maximum output power (P_{mpp}) of 1.57 W, short-circuit current (I_{sc}) of 3.13 A, open-circuit voltage (V_{oc}) of 0.63 V and temperature coefficient of -0.37 %/°C. By having three quarterssize PV cells, the P_{mpp} and I_{sc} should be equal to one-third of the corresponding full-size cells, whereas the V_{oc} should remain the same. Furthermore, a low iron solar glass cover (from Scheuten Glas) and a Plexiglas side gable protection with a thickness of 4 mm have been added to the collector design concept. The emissivity, thermal conductivity and transmittance of glass cover are 84 %, 1 W/m.K and 91 %, respectively. For Plexiglas side gable protection above mentioned values are 94 %, 0.18 W/m.K and 92 %, respectively.

4. Description of Testing Facilities

4.1. Solar Laboratory of University of Gävle (HiG) (Sweden)

The DM-CPVT has been evaluated, built, and installed in the outdoor testing laboratory with a variable southoriented collector tilt angle (β) depending on the nature of the tests. The test setup apparatus consists of a solar collector closed-loop and a domestic hot water open-loop. Furthermore, the solar collector loop relates to the HTF

¹ Distance between top receiver side and glass cover.

² Distance between the bottom receiver side and the mid reflector (middle of section A).

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flowing between the collector and heat exchanger, supplied by a fixed flow rate. A mixture of 80% of pure water and 20% of ethylene glycol (with a heat capacity of 2200 J/kg.K) has been used as HTF (overall heat capacity of 3813 J/kg.K). The test stand consists of a hydraulic and electric circuit designed for performance characterization and has been used for both electrical and thermal measurements which measures inlet, outlet and ambient temperature, pressure, flow rate, and global and diffuse solar radiation. The closed-loop is composed of programmable logic controller, automated flow control, collector inlet temperature control, temperature measurement tool, vacuum degasser and stainless-steel piping. The solar collector test facility is composed of a hydraulic and electrical and thermal performance characterization, several testing measurement equipments have been used, such as two KippZonen (CMP3 for diffuse and CMP6 for global radiation) pyranometers (installed in the same plane as the solar collector), IV tracer, ambient and HTF temperature sensors, and flowmeters. The testing equipment is connected to a CR1000 datalogger from Campbell Scientific that monitors, records and processes the data with time-step measurements of 30 sec. All the measurements were then treated as 10 minutes average data to compress and increase data accuracy. Figure 2 shows the CPVT solar collector test apparatus located in the Solar Laboratory of the University of Gävle (HiG).



Figure 2. Technical drawing of the hydraulic rig composed of several temperature and pressure sensors.

The hydraulic rig consists of several temperature and pressure sensors, a heat exchanger, a vacuum degasser, an expansion vessel, a mixing tank (for a more homogeneous temperature) and a heater for constant inlet temperature (Figure 2). The setup measures inlet, outlet and ambient temperature, pressure, flow rate, and global and diffuse solar radiation which are for both electrical and thermal measurements. For the thermal performance investigation, in each measurement timetable, the inlet collector temperature was constant (to reach the yield) and the collector's outlet temperature was measured to investigate the collector's thermal function. Table 2 presents both the thermal and electrical measurement components accuracy.

Thermal measurement equipment	Value	Accuracy	
Flow rate ṁ [L/m]	0.5-10	±1.5 %	
Temperature difference ΔT [°C]	0-90	±0.04 %	
Pressure interval ∆P [Bar]	Up to 6	±1.5 %	
Heater [°C]	10-90	±0.04 %	
Pressure transmitter [Bar]	6	±1 %	
Electrical measurement	Data	Allowed	
equipment	Daia	Deviation	
Pyranometer CMP3 [W/m ²]	Up to 2000	±1.5 %	
Pyranometer CMP6 [W/m ²]	Up to 2000	±1 %	
IV Tracer [I] [V]	-	0.1 %	

Table 2. Thermal and electrical measurement components and respective accuracy deviation in comparison to the manufacturer datasheets.

4.2. Solar & other Energy Systems Laboratory (SESL) at the NCSRD (Greece)

The DM-CPVT has been moved to Greece at the NCSRD facilities (latitude/longitude: +37°58'/+23°43') for performance assessment during the period of September-October 2020. The test-bench of the PVT collector includes a two-axis tracker, a temperature preparation unit (includes an air-source heat pump and a storage tank) and a pumping station for adjusting the temperature of the heat transfer fluid and fixing the flow rate equipped with several pneumatic valves and mixing circuits. The collector has been mounted and fastened on the tracker with the inlet and

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outlet pipes (from one side of the collector) connected with the pumping station. Temperature sensors (4-wire PT100, standard uncertainty 0.05 K) have been installed at the inlet/outlet piping of the collector to measure the water/glycol temperature. These piping parts have been insulated, once the charging and venting processes have been accomplished. An electromagnetic flowmeter with an accuracy of 1% measures the HTF flow rate and two pyranometers (CMP11, accuracy 1.3%) measure the global and diffuse radiation. An IV tracer was used to measure the voltage and current at MPPT conditions. The pressure in the piping was also monitored frequently, to make sure that no air is trapped. The test stand can test (electrical and thermal performance test) at tracking mode, in which the incidence angle does not affect the results (i.e., solar irradiation is always perpendicular to the surface). These tests have been conducted for 5 temperature levels, starting from the ambient (~22 °C) and reaching almost 80 °C. During the tests at each temperature level, the measurements have been recorded, but they have been included in the processing, only when the temperature deviation over a 10-minute duration was less than 0.1 K. This testing protocol is based on the ISO 9806:2017 standard testing specifications for solar thermal collectors and practically ensures a steady-state test and increased reliability. The tests at each temperature level have been finished once 4 of these 10minute periods were achieved for each level, with the measurements then filtered and averaged. Figure 3 shows the CPVT solar collector test apparatus located in NCSRD (Greece) and the Solar Laboratory of the University of Gävle (HiG, Sweden).



Figure 3. CPVT solar collector test apparatus is located in the Solar Laboratory of the University of Gävle (left image) and at NCSRD (right image).

5. Performance Assessment of DM-CPVT

The electrical performance of the CPVT collector was characterized according to IEC 62108 (2007) in Sweden, while the thermal performance was characterized according to ISO 9806:2017 (by Steady-state (SS) test methods) in Sweden and Greece.

5.1. Thermal & Electrical performance, Sweden

Results from performance assessment in Solar Laboratory of HiG showed that electrical peak efficiency of 10.8% ($R^2 = 0.999$) for a module temperature of 25 °C has been achieved. The steady electrical peak efficiency for higher temperatures gives a temperature dependence coefficient of around 0.49 %/°C. At HiG, the heat loss coefficient U_1 , reached a value of 4.48 W/m².K, whereas the optical efficiency η_0 reached a value of 63.6 % (divided in 53.1 %_{th} and 10.5 %_{elect}, $R^2 = 0.997$) has been obtained per gross area (presented in Figure 4).



Figure 4. Experimental overall efficiency per gross area measured at HiG, Sweden.

5.2. Thermal performance, Greece

The performance assessment developed at NCSRD showed that the peak thermal power of the collector for beam radiation of 850 W/m² and a diffuse radiation of 150 W/m² is 1332 W. This power is obtained for a mean collector temperature equal to the ambient temperature (T_m - T_a = 0 K).

The steady-state test method was adopted for the performance tests performed at the NCSRD in Greece. The measured data during the PVT collector tests have been filtered, averaged and presented in five temperature levels in Table 3.

$T_{m}\left(^{o}C\right)$	G (W/m ²)	$G_d (W/m^2)$	M (l/h)	$T_a(^{o}C)$	$T_{i}\left(^{o}C\right)$	T ₀ (°C)
26.46	966.5	102.9	198.7	24.9	23.5	29.5
26.60	1004.9	118.5	198.4	24.9	23.5	29.7
26.55	1014.5	144.1	198.7	24.9	23.5	29.6
26.53	996.9	112.6	198.4	24.8	23.5	29.6
39.15	874.3	62.0	196.5	24.4	36.8	41.5
39.12	897.0	63.6	196.4	24.3	36.6	41.6
39.73	1037.8	108.1	194.6	24.9	36.9	42.6
39.50	1044.2	89.2	194.7	24.4	36.6	42.4
48.74	1000.3	69.9	191.9	24.8	46.1	51.3
48.69	989.6	68.3	192.8	24.5	46.1	51.3
50.52	1037.3	75.1	190.7	24.0	47.9	53.2
50.45	1028.3	69.2	190.7	23.8	47.9	53.0
59.89	1006.7	69.6	189.7	25.3	57.6	62.2
60.02	1008.8	67.8	189.2	25.3	57.7	62.4
61.62	971.9	137.0	191.1	21.0	59.5	63.8
61.57	968.4	120.6	191.7	20.9	59.5	63.7
76.46	975.4	112.3	186.8	22.4	74.8	78.1
76.69	1065.3	203.6	187.5	22.6	74.8	78.6
76.70	1068.4	204.9	188.2	22.7	74.8	78.6
76.95	1105.8	257.7	188.2	23.6	75.0	78.9

Table 3. Recorded test results of the PVT collector at NCSRD.

According to the calculation from the test data, based on the gross area of the collector, the magnitudes of each equation of the thermal performance model are shown in Table 4. A_i is the new reference surface and the values are adjusted and multiplied with the surface ratio A_i/A_G , when the aperture area or the area that would correspond to the commercial product is used.

 Table 4. Parameter values and standard deviation of the performance correlation of the PVT collector at NCSRD.

1 st Order	Value	Std	Units
$\eta_{0,hem}$	0.515	0.004	-
U_0	4.422	0.136	W/m^2K
2 nd Order	_		
$\eta_{0,hem}$	0.505	0.004	-
α_1	3.216	0.371	W/m^2K
α_2	0.021	0.006	W/m^2K^2
4 th Order	_		
$\eta_{0,hem}$	0.510	0.005	-
α_1	4.536	0.700	W/m^2K
α ₂	-0.028	0.024	W/m^2K^2
α_8	0.000009	0.000004	W/m^2K^4

For a parameter to be statistically important, the value of each parameter must be positive and greater than three times its standard deviation (According to the ISO 9806:2017); Therefore the 4th order equation includes a negative a_2 value, which does not have a physical meaning, and on top of that the standard deviation of this parameter is about the same as its value. So, the preferred equation to be used is the 2nd order, which has a good accuracy over the whole range of temperatures tested, from the ambient up to 80 °C.

The function of the temperature difference based on the test data and the 2^{nd} -order equation as the collector performance is shown in Figure 5 (A).



Figure 5. A) Collector performance as a function of the temperature difference at NCSRD (B) Heat gain of the collector for three typical solar irradiation levels at NCSRD.

In addition, the peak thermal power of the collector is 1332 W for beam radiation of 850 W/m² and a diffuse radiation of 150 W/m². This power is obtained for a mean collector temperature equal to the ambient temperature (T_m - T_a =0 K). Second-order performance correlation of the collector showed that the heat loss coefficient U_I , has a value of 4.42 W/m².K and η_0 , has a value of 62.7% (divided in 51.9 %_{th} and 10.8 %_{elect}) based on the gross area, which holds a good accuracy over the whole range of temperatures tested, from the ambient up to 80°C.

Finally, the procedure of ISO 9806:2017 includes an indicative collector heat gain according to the available solar irradiation, divided into a blue sky, hazy sky and grey sky. Figure 5 (B) shows the heat gain of the collector under these three typical scenarios.

5.3. Electrical performance, Greece

Results from performance assessment in Solar Laboratory of NCSRD showed that electrical peak efficiency of 10.5% ($R^2 = 0.999$) for a module temperature of 25 °C has been achieved. When the impact of the IAMs is minimal (they are equal to unity) in tracking mode, the electricity generation is monitored using an IV tracer, which changes the voltage and current to find the condition that produces the peak power. Once the thermal performance has achieved a steady-state condition, this measurement is extremely quick (just a few seconds are required). The tracer sweeps the whole IV curve before identifying the MPPT point. This procedure is performed for each of the collector's four PV rows. The readings of the four IV curves for each row and temperature level are measured in tracking mode. Figure 6 shows an example of the IV curves, with the MPPT for each of the four PV strings at two temperature levels: ambient and 60°C. It is the ones that are positioned at the rear side of the collector that produces the most power

because they receive concentrated solar irradiation.



Figure 6. IV curves of the four PV rows of the collector for a temperature level equal to the ambient one (top) and 60 °C (bottom).

The voltages of the four rows at MPPT are similar, but the currents of the rows positioned on the backside of the receiver are significantly higher. The four panels of the table are labelled as follows:

- Panels 1 & 3 are the back ones (with reflected irradiation);
- Panels 2 & 4 are the front ones (with non-reflected irradiation);
- Panels 1 & 4 are the top ones;
- Panels 2 & 3 are the bottom ones.

Figure 7 shows the test results for the five temperature levels for the PVT collector's electricity production in tracking mode. The measurements at a mean collector temperature of 26 °C were repeated twice to ensure the data's accuracy at this temperature, as the peak electrical power is specified at a similar temperature, which is 25 °C at standard test conditions (STC). The solar irradiation is similar at all temperatures, and that the temperature has a significant impact on the amount of energy produced, as can be seen at all temperature levels. Since solar irradiation is similar for all testing settings, increasing collector temperatures reduce power output almost linearly.



Figure 7.Effect of the collector temperature on the power output.

5.4. IAM tests

To identify the IAMs in both transversal and longitudinal directions, the above performance tests that have been conducted at tracking mode, the collector is adjusted to incidence angles, corresponding to several transversal and longitudinal angles of incidence by the tracker. These are essential to achieve the annual performance of the PVT collector at different angles.

When all IAM values are equal to 1, means that the performance parameters of the collector are fixed with the 2ndorder equation presented previously. For the identification of the IAM values, all tests have been performed during clear days, when the position of the collector was manually varied, to follow the sun movement, and keep either a transversal angle or the longitudinal angle equal to zero. To reach a steady-state thermal condition, the collector positioning should be controlled accurately. So when the solar angle and irradiation are more or less constant for 2-3 hours (typically during the noon), which is adequate to reach a steady-state condition.

According to the ISO 9806:2017, here the estimation of a single IAM value has been extended to three transversal and three longitudinal IAM values. For each angle that was swept, the other angle was kept equal to zero. Therefore, the pairs of transversal/longitudinal angle modifiers obtained are 0/30, 0/40, 0/50, 30/0, 40/0, and 50/0 degrees. To evaluate the electrical IAMs, another angle of 15° has been obtained for both directions (0/15 and 15/0 deg.).

The IAM tests have been done on October 14th 2020 in Greece. The thermal performance should be stabilized and reach a steady-state condition for 10 minutes, with the recorded test data during that period further processed. The test data are shown in Table 5.

Table 5. Steady-state test data for the calculation of the thermal IAMs in Greece

Time / duration	Incidence irradiation (W/m ²)	Diffuse irradiation (W/m ²)	Flow rate (l/h)	Ambient temperature (°C)	Inlet temperature (°C)	Outlet temperature (°C)	Angle, θ (deg.)
11:56-12:06	878.1	79.7	199.0	23.1	21.4	26.7	30 trans.
10:06-10:16	858.6	68.2	199.4	21.7	19.5	23.9	30 long.
11:24-11:35	794.9	76.2	199.1	22.8	21.4	26.0	40 trans.
10:45-10:56	801.3	70.0	199.6	22.2	21.1	24.3	40 long.
13:46-13:56	684.2	72.0	194.6	25.4	21.6	25.4	50 trans.
10:24-10:34	698.9	66.6	200.0	22.1	19.4	22.2	50 long.

The thermal IAMs are calculated by eq. 8 and the previous table data. The specific heat capacity (c_p) and the density used to calculate the mass flow rate (\dot{m}) correspond to the water/glycol mixture at the mean collector temperature.

$$K_b(\theta) = \frac{\frac{\operatorname{in} c_p \cdot (T_o - T_i)}{A_g} + \alpha_1 \cdot (T_m - T_a) + \alpha_2 \cdot (T_m - T_a)^2}{G \cdot \eta_{0,hem}}$$
eq. 8

The resulting thermal IAMs for both transversal and longitudinal directions based on the test data are shown in the following Figure 8.



Figure 8. Thermal IAMs (longitudinal and transversal) based on test data direction for both HiG (Sweden) and NCSRD (Greece) laboratories.

In Figure 9 are shown the IAMs for the transversal and longitudinal angles and a standard calculation formula suggested by Ambrosetti (Rasmussen et al. 2020): $K_b(\theta) = 1 - \tan^k \left(\frac{\theta}{2}\right)$, where the parameter k determines the slope of the function. This parameter is the average from the ones calculated based on the experimental values, using eq. 9, and is equal to 2.85 for the transversal and equal to 1.267 for the longitudinal angle.



Figure 9. Electrical IAMs for the transversal and the longitudinal direction for both HiG (Sweden) and NCSRD (Greece) laboratories.

The correlation presented in Figure 9 for both testing results in Sweden and Greece, shows a minor deviation in the transversal direction around 20-30° as it falls under the acceptance angle of the CPC reflector geometry. Nevertheless, the agreement is almost perfect between a tracking system used at NCSRD and a hydraulic manual system at HiG. The longitudinal angle closely follows a symmetric profile and can be very well approximated by the Ambrosetti formula with the parameter *k* of 2.85. This formula can be then used to calculate the IAM at the transversal direction for the whole range of incidence angles with very good accuracy.

However, the longitudinal IAMs follow a different pattern due to the concentrator that introduces asymmetric effects, with the available IAMs at that direction used to validate a ray-tracing model of the collector, and thus expand the calculation method over the whole range of angles. In eq. 10 and eq. 11, the diffuse incidence angle modifier constant (K_d) is calculated.

$$K_{d} = \frac{1}{W} \sum_{\theta, \gamma = 0^{o}}^{90^{o}} K_{b(\theta, \gamma)} \cdot \sin(\theta) \cdot \cos(\gamma)$$

eq. 10

 $W = \sum_{\theta, \gamma=0^o}^{90^o} \sin(\theta) \cdot \cos(\gamma)$

Where K_d is 0.717.

6. Conclusions

DM-CPVT collector geometry showed to be the most promising geometry due to the lower shading impact of this geometry at incidence angles higher than 45°. Moreover, the study showed that the longitudinal direction is closely related to the shading effect, as partial shadowing is substantial from 30° onwards. It is important to state that in a PVT collector with concentration, it is necessary to 'sacrifice' (to some extent) the thermal yield to increase the electrical yield, and for this reason, geometry DM-CPVT collector geometry has been the recommended geometry for the CPVT solar collector.

The electrical performance of the CPVT collector was characterized according to the international standards presented in the IEC 62108 (2007), while the thermal performance was characterized according to ISO 9806:2017 (by Steady-state (SS) test methods). Results from performance assessment in Solar Laboratory of both HiG and NCSRD showed that electrical peak efficiencies of 10.8% and 10.5% ($R^2 = 0.999$) for a module temperature of 25 °C have been achieved, respectively. The steady electrical peak efficiency for higher temperatures gives a temperature dependence coefficient of around 0.49 %/°C. At HiG, the heat loss coefficient U_1 , reached a value of 4.48 W/m².K, whereas the optical efficiency η_0 reached a value of 63.6 % (divided in 53.1 %_{th} and 10.5 %_{elect}, $R^2 = 0.997$) has been obtained per gross area. Results from performance assessment at NCSRD showed that the peak thermal power of the collector for beam radiation of 850 W/m² and a diffuse radiation of 150 W/m² is 1332 W. This power is obtained for a mean collector temperature equal to the ambient temperature (T_m - T_a = 0 K). Second-order performance correlation of the collector showed that the heat loss coefficient U_1 , has a value of 4.42 W/m².K and η_0 , has a value of 62.7% (divided in 51.9 %_{th} and 10.8 %_{elect}) based on the gross area, which holds a good accuracy over the whole range of temperatures tested, from the ambient up to 80°C.

7. Acknowledgments

This work has been performed within the RES4BUILD project (Renewables for clean energy buildings in a future power system) – Horizon 2020 program, Grant Agreement no. 814865. The authors would like to express their gratitude to Razif Kunjumon from MG Sustainable Engineering AB for his useful help and discussion during the project.

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Effect of a Wavy Tape Insert and Glass Cover on the Performance of a Photovoltaic Thermal System

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Abstract

Glazed photovoltaic thermal (PV/T) systems compared to unglazed ones provide higher thermal efficiency but reduced electrical efficiency. Thus, to improve the electrical efficiency while keeping the merit of a glazed system, this study equips the PV/T system with a wavy tape insert to augment the heat transfer to the coolant fluid and in turn, reduce the PV cell temperature. This study explores the effect of a wavy tape insert on both glazed and unglazed PV/T systems over the average of selected days in summer at Mashhad, Iran, using computational fluid dynamics. It is found that the insert reduces the PV cell average temperature during the day by 5.9 and 7.1 K for unglazed and glazed modules, respectively, but has a negligible effect on the pump power consumption, which leads to an overall efficiency gain of 11.43% and 13.46% compared to the base case, in that order. Thus, the insert improved the electrical efficiency of glazed PV/T systems, while keeping the merit of the glazed system in increasing the thermal efficiency. The other important issue for solar cells is the temperature distribution within the module which may lead to serious thermal stress and strain. It has been found that using a wavy tape insert can considerably reduce the spatial temperature variation of the cell temperature and consequently improve their lifetime.

Keywords: Glazed photovoltaic thermal system, Unglazed photovoltaic thermal system, mixing devices, Wavy tape insert, computational fluid dynamics, discrete ordinate method.

1. Introduction

Over the years, different studies have been carried out to exploit clean solar energy. The main reasons for these activities are problems such as warming of the earth, rising oil prices, and the predicted end of nonrenewable energy in the near future. International Energy Agency (IEA) predictions on oil supply show that crude oil and petroleum products are expanding, and there will be a decline in crude oil consumption by 2030 (Aleklett et al., 2010). Two of the widespread technologies for utilizing solar energy are photovoltaics (PVs), and solar collector systems, which directly convert sunlight into electricity or thermal energy, respectively. In recent decades PV systems have developed dramatically and, significantly, their cost has reduced (Comello et al., 2018).

According to previous investigations, rising PV plate temperature reduces its electrical conversion efficiency (Skoplaki and Palyvos, 2009). However, a combination of the PV unit and a thermal collector, which is known as a photovoltaic thermal (PV/T) system will reduce the PV cell temperature. Furthermore, fixing a thermal collector below the PV module can increase the PV system lifetime, reduce the installation space, and raise the overall efficiency owing to the utilization of the thermal energy (Moradgholi et al., 2018). Different methodologies have been proposed and developed to improve the performance of PV/T systems, for instance: augmentation of coolant fluid thermophysical properties by using nanofluids (Maadi et al., 2017a; Maadi et al., 2017b), implementation of Phase Change Material (PCM) (Kazemian et al., 2021), an increase in the number of risers in a given total mass flow rate (Maadi et al., 2019c), and employing a thermoelectric device in the system (Kolahan et al., 2020).

One of the methods for increasing heat transfer in many applications is to insert mixing devices in the collector tubes, but these are rarely used in photovoltaic thermal (PV/T) systems. Using such devices in parabolic trough collectors (PTCs) can increase heat transfer about 20-300%, and 10-200%, for the laminar and turbulent regime, in that order (Sandeep and Arunachala, 2017). As their name implies, mixing devices increase mixing and in turn increase in the heat transfer rate (Jaisankar et al., 2011). The price paid is an increase in the pressure drop, which means more pump power is needed (Bellos et al., 2017) and must be considered in optimizing the thermal

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performance. Recently, Maadi et al. (2020) scrutinized the effect of conical-leaf inserts in different geometrical parameters and various operating conditions on the performance of an unglazed PV/T system. The inserts reduced the cell temperature by up to 7 K, which, in turn, lead to considerable improvement in electrical and thermal efficiencies. Moreover, it has been found that the pump power was negligible compared to the electrical output power. In another study by Maadi et al. (2021), the effect of a wavy-tape insert along with Al_2O_3 -water nanofluid for an unglazed PV/T system was examined. A tube equipped with a wavy-strip insert, and a nanofluid with a volume fraction of 3% improved the thermal and electrical efficiencies by 12.06% and 3.5% compared to a water-based PV/T module with the bare tube, respectively.

Another method to increase thermal efficiency is trapping the light by using one or more glass covers. Installation of a glazed cover above the PV/T system (Glazed PV/T system) on the one hand reduces the total heat transfer loss to the surroundings, which increases the thermal efficiency of the system. On the other hand, the electrical efficiency reduces as the cells experience higher temperature, and a portion of incident solar irradiation is reflected from the cell surface and is absorbed by the glass cover (Chow et al., 2009; Kazemian et al., 2018).

Based on the literature review, using an insert in the coolant tube can lead to a considerable improvement of the tube's heat absorption rate. The use of mixing devices has advantages such as: ease of installation and removal from a bare tube, a negligible effect on the strength of the original tube, and cheapness. Nevertheless, there is little knowledge of the integration of mixing devices with PV/T modules to increase their performance. To this end, this study investigates the effect of a glass cover and a wavy tape insert simultaneously on the performance of the PV/T module. A 3D model is presented with the simulation of the entire layers of the PV/T system along with thermophysical and optical properties. For simulating the optical behavior of different components of the PV/T module, the discrete ordinate (DO) method, along with the solar ray tracing algorithm, is employed. Furthermore, the proposed simulation has sufficient accuracy to capture the exchange of short to long-wavelength radiation in the air gap between the glass cover and the surface of the PV cells. In other words, by using the two-band radiation DO model, the greenhouse effect is considered. According to the literature review, this is the first time the proposed simulation is taken into account for comparing the glazed and unglazed PV/T systems.

2. Numerical simulation

The governing equations for modeling the fluid in steady state, are as follows.

Continuity:

$$\vec{\nabla} \cdot \left(\rho_f \vec{V}_f\right) = 0 \tag{eq. 1}$$

Momentum:

$$\vec{\nabla}.\left(\rho_f \vec{V}_f \vec{V}_f\right) = -\vec{\nabla}P_f + \vec{\nabla}.\tau_1 + \rho_f \vec{g}$$
(eq. 2)

Energy:

$$\vec{\nabla}.\left(\rho_f C_{p,f} T_f \vec{V}_f\right) = \vec{\nabla}.\left(k_f \vec{\nabla} T_f\right)$$
(eq. 3)

where ρ , \vec{V} , P, τ_1 , C_p , T, g, and k are density, velocity, pressure, shear stress, specific heat capacity, temperature, gravity, and thermal conductivity, respectively. Subscript *f* specifies the fluid (air or water). For the glazed PV/T module, as shown in Fig. 1, there is free convection inside the gap, which is simulated with the Boussinesq approximation. In this model, density is considered constant in all governing equations except for the buoyancy term in the momentum equation (Maadi et al., 2019b):

$$(\rho_{air} - \rho_{amb})g \approx -\rho_{amb}\beta(T - T_{amb})g \tag{eq. 4}$$

In (eq. 4), in order, ρ_{amb} , and β refer to the air density at the ambient temperature (T_{amb}) and the thermal expansion coefficient. The formula for solving the conduction heat transfer in solid part is (Maadi et al., 2019b):

$$k_s \nabla^2(T_s) - \gamma e'_{elec} + S_h = 0 \tag{eq. 5}$$

where γ is the constant coefficient, equal to one for the PV cells, and zero for the remaining solid parts. The subscript s refers to the solid layers. The second term in (eq. 5) indicates the output of electrical power per unit volume of the PV cells. The electrical power of the PV cells is derived from a well known relation (Skoplaki and Palyvos, 2009):

$$E_{elec} = \dot{S} \eta_{ref} (1 - \beta_{ref} (T_{PV} - T_{ref})) P_a$$
(eq. 6)

where, β_{ref} , T_{ref} , η_{ref} , and T_{PV} are reference temperature coefficient, reference temperature, reference cell efficiency, and PV cell temperature respectively. P_a is called the packing factor, which is the ratio of the area of the solar cells to the PV module area (Skoplaki and Palyvos, 2009). In (eq. 6), \dot{S} denotes the effective absorbed solar irradiance by the solar cells, and is given by (Maadi et al., 2019b) as

$$\dot{S} = \tau_g \, \bar{\alpha}_{PV} \, G_{sun} \tag{eq. 7}$$

where, τ_g , $\bar{\alpha}_{PV}$, and G_{sun} are glass transmittance, the effective absorptance of PV cells, and incident solar radiation, respectively.

Fig. 1 elaborates the main heat transfer mechanisms in both glazed and unglazed PV/T systems. The glass cover has different transparency at different light wavelengths. In other words, it has spectral optical properties. For the long-wavelength region it is almost opaque, while for the remaining wavelengths, it is semi-transparent. Therefore, according to Fig. 1 for the glazed PV/T system, the short spectrum irradiation passes through the glass cover and is incident on the PV cells ($G_{t,g}$). Some part of it is absorbed by the cells ($G_{a,PV}$), and the remainder reflects as a long wavelength ($G_{r,PV}$) (Maadi et al., 2019b). As shown in the figure, most of this reflected light is trapped inside the gap zone and gives rise to the greenhouse effect (Maadi et al., 2019b). The greenhouse effect is one of the essential differences between the glazed and unglazed systems. As clearly seen in Fig. 1, the glass cover results in a portion of solar irradiance being reflected to the surrounding ($G_{r,g}$), and a very small amount of it is absorbed by the glass cover ($G_{a,g}$); hence, in contrast to the unglazed one, less solar irradiance reaches the cells. Moreover, in the glazed PV/T system compared to the unglazed one, the thermal energy loss to the surrounding is reduced. In Fig. 1 q_{rad} refers to the thermal radiation either in the gap or to the surrounding, and q_{conv} refers to the forced convection of the exterior surface.



Fig. 1: The main heat transfer mechanisms in both glazed and unglazed PV/T modules.

For simulating the optical behavior of different components of the PV/T module, the DO technique, along with
the solar ray tracing algorithm, is employed. Furthermore, the simulation has sufficient accuracy in simulating the exchange of short wavelength to long wavelength radiations to capture the greenhouse effect. Further information is provided in the study of Maadi et al. (2019b).

In (eq. 5), S_h is a heat source due to the incident solar irradiance absorbed by the solid layers shown in Fig. 2. For the glazed PV/T system, S_h is determined by the Radiative Transfer Equation (RTE), along with solar ray tracing, which simultaneously solves the continuity, momentum, and energy equations. In this study, the DO radiation model is adopted to solve the RTE for a finite number of discrete solid angles, each related with a vector direction fixed in the global Cartesian system (x, y, z). Further information is given by (Modest, 2013).

In order to model the wavelength-dependent optical properties, the RTE for the spectral intensity $I_{\lambda}(\vec{r},\vec{s})$ must employ non-gray radiation at position \vec{r} in the direction \vec{s} , which is derived as (Maadi et al., 2019b):

$$\vec{\nabla}.\left(I_{\lambda}(\vec{r}.\vec{s})\vec{s}\right) + (\sigma_{\lambda} + \sigma_{s})I_{\lambda}(\vec{r}.\vec{s}) = \sigma_{\lambda}n^{2}I_{b\lambda} + \frac{\sigma_{s}}{4\pi}\int_{0}^{\pi_{h}}I_{\lambda}(\vec{r}.\vec{s})\Phi(\vec{s}.\vec{s}')d\Omega' \qquad (eq. 8)$$

where σ_{λ} , $\vec{s'}$, σ_s , Ω' , Φ , n, and $I_{b\lambda}$ are spectral absorption coefficient, scattering direction vector, scattering coefficient, solid angle, phase function, refractive index, and the blackbody intensity which is given by the Planck function, respectively. Furthermore, $(\sigma_{\lambda} + \sigma_{s})$ denotes the optical thickness or capacity of the medium. The total intensity $I_{\lambda}(\vec{r},\vec{s})$ in every direction of \vec{s} at position \vec{r} over the wavelength regions is calculated by summation of over each wavelength band as (Maadi et al., 2019b):

$$I_{\lambda}(\vec{r}.\vec{s}) = \sum_{k} I_{\lambda_{k}}(\vec{r}.\vec{s}) \,\Delta\lambda_{k} \tag{eq. 9}$$

In (eq. 9) for each band, the optical properties are considered as wavelengthindependent (gray). The black body emission over each wavelength interval per unit solid angle evaluated as (Maadi et al., 2019b):

$$E_b(\lambda,T) = [F(0 \to n\lambda_2 T) - F(0 \to n\lambda_1 T)]n^2 \frac{\sigma T^4}{\pi}$$
(eq. 10)

In

(eq. 10) according to the Planck distribution, $F(0 \rightarrow n\lambda T)$ is the ratio of radiant energy of a black body over the wavelength interval from 0 to λ at temperature T emitted in a medium with the refractive index n.

Since the PV cells are opaque, the radiation incident in each band on the surface is calculated as (Maadi et al., 2019b):

$$\dot{q}_{inc.PV\lambda} = \Delta \lambda \int I_{in\lambda} \vec{s}. \vec{n} d\Omega$$
(eq. 11)

and net radiative energy flux at each wavelength from the PV cells surface is derived as (Maadi et al., 2019b):

$$\dot{q}_{out,PV,\lambda} = (1 - \varepsilon_{PV,\lambda})q_{PV,inc,\lambda} + \varepsilon_{PV,\lambda}[F(0 \to n\lambda_2 T) - F(0 \to n\lambda_1 T)]n^2 \sigma T_{PV}^4 \qquad (eq. 12)$$

where $\varepsilon_{PV,\lambda}$ and σ are the PV cells emissivity in each band, and the Stefan-Boltzmann constant equal to $5.67 \times 10^{-8} W/m^2 K^4$, respectively.

Fig. 2 demonstrates the schematic of the proposed PV/T system along with its boundary conditions and components. In this study, we considered a PV/T module with five straight tubes, N=5 of diameter 0.05m. The entire characteristics of the simulated PV/T system are presented in Tab. 1 and thermophysical properties of different components can be found in the study of Maadi et al. (2020), and their optical properties were given in the study of Maadi et al. (2019a). In this study, the PV/T module without a glass cover and using the plain tube is called the base case, and the effect of the wavy tape insert and glass cover on the PV/T efficiencies are compared with it.

Component	Parameter	Definition	Value	Unit
Glass cover	t_g	Glass thickness	0.004	т
Air gap	t _{air-gap}	Air gap thickness	0.012	m
Encapsulated Si	L	Length	2	m
	W	Width	1.5	m
	t_{eva}	EVA layer thickness	0.0005	m
	t_{arc}	ARC layer thickness	8×10^{-8}	m
	<i>t_{si}</i> Si layer thickness		0.0003	m
	t_{tedlar}	Tedlar layer thickness	0.0001	m
Absorber plate	t_{abs}	Absorber layer thickness	0.002	m
Tube	D	Diameter	0.05	m
	t_t	Tube thickness	0.003	m
	Ν	Number of tubes	5	-
	S	Space between tubes	0.3	m

In this study, pure water is the coolant and its thermophysical properties are temperature-dependent (Maadi et al., 2019a). For evaluating the thermal radiation, the external radiation temperature is considered as sky temperature, which depends on the ambient temperature [59] according to

$$T_{sky} = 0.0552T_{amb}^{1.5}.$$
 (eq. 13)

For calculating the forced convection, the convective heat transfer coefficient is obtained by (eq. 14) [7].

 $h_{wind} = 2.8 + 3V_{wind} \tag{eq. 14}$

where V_{wind} is the local wind speed.



Fig. 2: Front view schematic of the proposed typical PV/T system along with its boundary conditions and perspective 3D view of the tube along with considered wavy tape insert.

2.1 Performance evaluation

For evaluating the performance of the PV/T module, we consider the thermal efficiency (η_{th}), electrical efficiency (η_{elec}), and overall efficiency (η_{ov}), defined as

$$\eta_{th} = \frac{\dot{m}C_{p.w}(T_{W.out} - T_{W.in})}{AG_{sun}} \tag{eq. 15}$$

$$\eta_{elec} = \frac{E_{elec} - E_{pump}}{AG_{sun}} \tag{eq. 16}$$

$$\eta_{ov} = \eta_{th} + \eta_{elec} \tag{eq. 17}$$

In (eq. 15), in order, \dot{m} , $C_{p,w}$, A, $T_{W.out}$ and $T_{W.in}$ refer to the inlet mass flow rate, water specific heat, module area, outlet, and inlet water temperature inside the tube. In (eq. 16), E_{pump} is the pump power consumption, which is calculated as (Maadi et al., 2019b):

$$E_{pump} = \frac{N\dot{m}\Delta p}{\rho_w \eta_{pump}} \tag{eq. 18}$$

where, in order Δp , and η_{pump} are the pressure drop in one tube, and pump efficiency. The pump efficiency is assumed to be 0.8 (Maadi et al., 2019a).

2.2 Grid independency

Fig. 3-a shows the 3D meshes. In order to balance the independence of the results from the size of the grids, against the execution time, different element numbers are examined. Outlet temperature and PV cell temperature are considered as the criteria to investigate grid independence. As illustrated in Fig. 3-b for the unglazed PV/T systems, by increasing the number of elements from grid 3 to 4, for both the plain tube and tube with a wavy tape, the outlet temperature and PV cell temperature remain constant. Therefore, we selected grid 3 with 800000 cells for the bare tube and 1600000 cells for the tube with a wavy tape, for the remainder of this study. Moreover, for the glazed PV/T system, the glass and gap layers required160000 more elements above the PV cells.

In the optical simulation, overall directions of $N_{\theta} \times N_{\phi}$ per wavelength band are solved. For three-dimensional calculations, a total number of $8 \times N_{\theta} \times N_{\phi}$ directions of the RTE equation are calculated. These control angles are then discretized by pixelation. Maadi et al. (2019b) recommended a pixelation and a division of 3×3 for a semi-transparent material. These values were used here.



Fig. 3: (a) the schematic of the grid for typical PV/T module and the insert tape (b) grid independence of the base case with and without wavy tape insert

2.3. Validation:

To verify the accuracy of the solution, the numerical data are validated with those available experimental data of the typical PV/T module (Bhattarai et al., 2012). The comparison is performed for the outlet and PV plate temperatures. As is depicted in Fig. 4, an average error below 3.8% and 4.9% in order, for electrical efficiency and thermal efficiency is obtained. Therefore, the proposed numerical model has sufficient accuracy in modeling optical and thermal performance.



Fig. 4: Validation of the current numerical model with experimental data of thermal and electrical efficiencies of the PV/T module.

3. Results and discussion

The wavy tape insert in the current study is the optimal configuration of Zhu et al. (2016). The evaluation is done on the average daily variation on selected days in summer at Mashhad, Iran (see Fig. 5) (Sardarabadi et al., 2017). Fig. 6 shows the daily variation of T_{out} and the T_{PV} for the base case, and both glazed and unglazed PV/T systems with wavy tape insert. This figure reveals that encapsulating a PV/T system with a glass cover increases the T_{out} and the T_{PV} ; however, at the beginning and end of the day when the insolation is low, the glass cover has little effect on the system temperature. The figure shows the insert reduces the mean T_{PV} during the day by 5.9 and 7.1 K for unglazed and glazed modules, respectively, and in turn, increases T_{out} . The reduction in the T_{PV} is more pronounced during peak insolation (hour 13:00), with a 6.8 and 8.2 K decrease for unglazed and glazed PV/T systems, respectively. The results demonstrate the pump power to the PV plate electrical output power, that is E_{pump}/E_{elec} , for all cases is less than 0.0001%, which is negligibly small. Fig. 7 demonstrates the average overall loss, thermal, and electrical efficiencies over the day for the three systems. A large portion of the incoming solar radiation is wasted, but the wavy tape insert considerably reduces the loss for an unglazed PV/T system by about 65%; while, encapsulating the PV/T system with a glass cover reduces the loss by 86%, due to the light trapping. As shown in Fig. 7, using a wavy tape insert improves the η_{th} for glazed and unglazed PV/T systems by 17.32%, and 13.06%, respectively. In terms of η_{elec} , this improvement is equal to 3.46% for the unglazed PV/T system; while, it can be seen that for the glazed PV/T system despite the insert, the η_{elec} is reduced by 5.3% compared to the base case. Indeed, for the glazed case, only 93% of the solar irradiance is transmitted through the glass cover and strikes by the PV cells, which means 7% of G_{sun} is lost and this causes the lower η_{elec} compared to the base case. Thus the additional cost and weight of the glass cover is combined with a lower η_{elec} , which can be counteracted by extracting further heat from the PV module to the coolant fluid. In terms of η_{ov} , the glazed PV/T system provides higher η_{ov} , and using the insert improves the unglazed and glazed PV/T modules by 11.43% and 13.46% compared to the base case, respectively.



Fig. 5: Average daily variation of G_{sun} and T_{amb} on typical days in August and September at Mashhad, Iran (Sardarabadi et al., 2017)



Fig. 6: Daily variation of outlet temperature and the PV temperature of the collector for the base case and both glazed and unglazed PV/T system integrated with wavy tape insert



Fig. 7: Comparison of the share of thermal, electrical, and overall loss efficiencies for the base case and both glazed and unglazed PV/T system integrated with wavy tape insert

The temperature distribution on the PV cells may lead to crucial thermal stresses, which in turn cause serious problems such as fractured cells, broken interconnections, reduction of cell power, and as well as lifetime

reduction. Fig. 7 illustrates the effect of the insert on the spatial variation of T_{PV} at three different hours 9:30, 12:30, and 15:30. As can be seen, the insert strikingly reduces the temperature gradient particularly around the peak insolation hour, 12:30. Fig. 8 shows the maximum temperature difference on the PV unit at the three different hours of the day. The insert reduces the maximum temperature difference, in order, for glazed and unglazed PV/T systems by 4.17 and 4.47 K at 9:30, 7.01, and 7.65 K at 12:30, and 6.2 and 6.46 K at 15:30. Therefore, the biggest reduction in thermal stress is obtained at the peak insolation.



Fig. 8: Surface temperature distribution of the PV cell at three different hours of the day at a) 9:30 b) 12:30 c) 15:30. The figures show the central one-fifth of the module with the coolant tube in the middle.



Fig. 9: Maximum temperature difference of the PV surface at three hours of the day

4. Conclusions

This numerical study considered the interaction of thermal and electrical performance of three photovoltaic/thermal (PV/T) systems: an unglazed PV/T system with the plain thermal collector tube (base case), a PV/T with a wavy tape insert for the glazed, and unglazed PV/T systems. A tube fitted with a wavy tape insert showed a reduction of PV cell temperature of the glazed PV/T system while keeping the merit of the glazed system in increasing the thermal efficiency. Using the insert reduces the average PV cell temperature during the day by 5.9 and 7.1 K for unglazed and glazed modules, respectively, and in turn, suppressing the energy losses by 65% and 86%, in that order. The reduction in PV cell temperature is more pronounced during peak insolation (hour 12:30). As 7% of the solar irradiance transmitted through the glass cover does not reach the PV plate, the electrical efficiency of the glazed PV/T system is lower than the base case. The reduction of the light incident on the PV plate lowers the electrical efficiency more than the reduction of the PV plate temperature caused by the insert in the collector tube which increases the electrical efficiency. It is worth mentioning the pump power is negligible compared to the PV plate's electrical output power. The results show that a wavy tape insert compared to the base PV/T system improves the thermal efficiency for glazed and unglazed PV/T systems by 17.32%, and 13.06%, respectively. From another perspective, using an insert for an unglazed PV/T system leads to considerable overall performance improvement (11.43%) compared to the base case with no mixing devices, while adding a glass cover makes the overall performance improvement a bit better (13.46%), at the penalty of additional weight and cost. Also, results show the insert reduces the spatial variation of cell temperature, which should reduce serious thermal stress and aging issues. To be commercially viable, the increase in cost and complexity of the PV/T module using a glass cover and/or wavy tape insert should be offset by the efficiency improvement; therefore, as a future recommendation, economic analysis for life cycle cost and cost payback for using a glass cover and/or wavy tape insert would be beneficial.

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Nomenclature

Quantity	Symbol	Unit
area	Α	m ²
specific heat capacity	C_p	$J kg^{-1}K^{-1}$
power output	Ε	${\rm W}m^{-2}$
solar irradiance	G _{sun}	$W m^{-2}$
radiation intensity	Ι	$W m^{-2}$
thermal conductivity	k	$\mathbb{W}m^{-1}K^{-1}$
mass flow rate	'n	kg s^{-1}
number of tubes	Ν	-
pressure	р	ра
packing factor	Pa	-
temperature	Т	К
gravity	g	$m s^{-2}$
velocity	V	m/s

Greek symbols

Quantity	Symbol	Unit
reference temperature coefficient	β _{ref}	-
thermal expansion	β	-
efficiency	η	-
effective absorptance	$\bar{\alpha}$	-
transmittance	τ	-
scattering coefficient	σ_s	-
phase function	Φ	-
solid angle	Ω'	-
density	ρ	${ m kg}m^{-3}$
difference	Δ	-
Absorptance	α	-
emissivity	3	-
absorption coefficient	σ	m^{-1}
difference	Δ	-

Abbreviations Preferred name Symbol Anti reflective coating ARC Discrete ordinate DO Ethylene vinyl acetate EVA Photovoltaic/thermal PV/T PV Photovoltaic Phase change material PCM RTE Radiative transfer equation Silicon Si Subscripts Quantity Symbol absorption а ambient ambblack body b fluid felectrical elec glass g inlet in overall ov outlet out photovoltaic pv pump pump reference ref sky sky solid s thermal th water Wwind wind wavelength λ

Appendix: Units and Symbols

A new concept of hybrid solar collectors: Polymeric heat exchanger for photovoltaic panels

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Abstract

Hybrid solar collectors generate electricity and heat at the same device. The present paper proposes a new concept of heat exchanger to be used in conventional photovoltaic (PV) modules, converting them into hybrid collectors. The proposed heat exchanger is made of corrugated polypropylene sheets, with multiple channels that occupies the full width of the PV module bottom surface. To characterize it, an experimental test bench was developed and numerical simulations using EES software were performed. The objective is to assess the heat exchanger performance and to attest that the energy balance modeling is suitable to predict the amount of heat flux absorbed by water. After carrying out experimental test configurations, the thermal contact resistance between the heat exchanger and the PV surface of $0.008 \text{ m}^2 \text{ K W}^{-1}$. The deviation between measured and calculated heat fluxes are about 12% and 8% for configurations without and with bottom thermal insulation, respectively.

Keywords: Hybrid solar collector, PVT modules, Polymeric heat exchanger, Heat transfer analysis

1. Introduction

Photovoltaic (PV) solar energy is obtained by the transformation of solar radiation into electrical energy using solar cells constructed with semiconductor materials, reaching efficiencies between 14% and 22% in commercially available panels (Blakesley et al., 2020). PV efficiency is defined by how effective the solar conversion process in electrical energy is (Pinho and Galdino, 2014). Nonetheless, there is a negative linear dependence on the efficiency of the PV panel with the increase of the operating temperature (Dubey et al., 2013). A cooling system can be adopted for the PV panels to counteract the loss of efficiency due to the temperature increase, and even, at the same time can harvest the rejected heat (Zarrella et al., 2019).

Different approaches exist for PV cooling, in active and passive ways, in the pursuit of reducing PV operating temperature and consequently increasing the PV conversion efficiency (Busson et al., 2021). The hybrid, or photovoltaic thermal (PVT), system generates electricity and supplies buildings with thermal energy while removing heat from the PV panel (Huide et al., 2017; Sultan and Efzan, 2018). The PVT modules may be cooled by water spray jets (Da Rocha et al., 2019) or by a heat exchanger, where a heat transfer fluid circulates, in contact with the rear face of solar cells (Preet, 2018). There are still options to remove heat from the PV module such as to submerge PV modules in water reservoirs, lakes, or rivers (Enaganti et al., 2020) and to float PV modules over water tanks (Busson et al., 2021).

Unlike PV systems, which are intended to work at low temperatures to not compromise efficiency, in solar thermal systems the objective is to reach a high temperature, which varies according to the application (Suman et al., 2015). Therefore, the challenge involving PVT modules lies in the development of a thermally balanced hybrid system, optimizing electrical and thermal efficiencies (Shyam et al., 2015), and, thus, obtaining a global energy

efficiency, thermal and electrical, higher than the two separate systems. Furthermore, the PVT efficiency depends on a combination of factors like working fluid, collector type, PV cells material, vitreous covering, flow configuration and heat exchanger type (Chow, 2010; Herrando et al., 2019).

Regarding working fluid, PVT can be cooled by air, water or other liquid. Despite the natural air circulation making the system cooling cheaper and simpler, it is less efficient in regions where the ambient temperature is typically higher than 20°C (Lamnatou and Chemisana, 2017), case of Brazil. In the case of PVs cooled by liquids circulating under their bottom surface, it is more common that water is used and flows through channels (Al-Waeli et al., 2019). Collectors cooled by water show better heat exchanger and lower PV operating temperature than collectors cooled by air (Moharram et al., 2013). However, a mixture with ethylene glycol is recommended in regions where temperatures below zero degrees are reached (Kazemian et al., 2018).

Concerning the heat exchangers used in hybrid collectors, two relevant parameters are the shape and amount of water flowing through channels. The absorber type can be sheet and tube, which is less costly, easier to manufacture, occupies less water capacity, or a thin channel below the full width of the PV rear surface, which enables a uniform temperature distribution, better heat transfer characteristics (Kumar et al., 2016). If multiple channels are chosen, then it may attain higher electrical and thermal efficiencies than sheet and tube configuration, however a good thermal contact between the absorber with multiple channels and PV bottom surface is harder to achieve (Kim and Kim, 2012a). Although, it has been determined that maximizing the transfer area is better than minimizing the contact resistance (Herrando et al., 2019). Each channel type can exhibit different shapes, like round, rectangular and others (Kim and Kim, 2012b; Kaewchoothong et al., 2021).

Most PVT manufacturers are European and produce uncovered water flat plate PVT collectors, the remaining is divided into 28% producing covered flat plate PVT collectors, 4% evacuated tube collector, 12% uncovered air flat plate collector and 8% concentrating PVT system (Ramschak, 2020).

The present paper introduces a new concept of a heat exchanger developed to be used in common PV panels, converting them into hybrid solar collectors. The proposed heat exchanger is made of corrugated polypropylene (PP) sheets and is installed at the rear face of the PV panel (Figure 1a). This heat exchanger is composed of 153 channels with a rectangular profile where water flows.



Fig. 1: New concept of heat exchanger installed on the PV module rear surface (a) and schematic representation of water circulation in the heat exchanger (b)

The main advantages of this system are the ability and the flexibility to convert any PV panel into a PVT panel and its low cost when compared to commercially available PVTs. The installation of the heat exchanger under the PV module rear surface is simple and fast, dismissing the use of extra tools where the PVT module will be located. Further the PP used to manufacture the heat exchanger is cheaper than other materials utilized commonly in PVTs and it is a suited material for long-term operation as solar collectors, like commercially available swimming pools heating solar collectors.

Figure 1b shows the water, in purple, flowing through the components of the heat exchanger: inlet pipe, distribution manifold and the channels in the corrugated PP sheet. The heat exchanger is fastened by transversal cantilever springs. The cantilever springs fit under the aluminum frame of the PV module and mechanically fastens the heat exchanger without interfering with the PV module and can be easily installed or removed. In this way, no permanent modifications are made to the panel and therefore, terms of warranty can be maintained by manufacturers. This paper has the objective to assess, through experimental tests and simulations, the characteristics of the heat transfer in the proposed heat exchanger for PV modules.

2. Methodology

To characterize the corrugated PP sheet heat exchanger characteristics, an experimental test bench was developed and numerical simulations using Engineering Equation Solver (EES) software were performed. The experimental stage is an indoor test bench where the heat is supplied to the heat exchanger by means of electrical heaters located on the top of a thick aluminum plate. The aluminum plate has the function of uniformizing the heat flow that reaches the heat exchanger, approximating what occurs during the real conditions of PVT panels under solar radiation. Temperature and mass flow measurements were performed as well as the dissipated electrical power. The purpose of the experiments on this test bench is to identify the thermal losses in the novel heat exchanger under different heat fluxes and water inlet temperatures.

Figure 2 shows a schematic representation of the indoor experimental test bench installed at the LEPTEN laboratories at the Federal University of Santa Catarina (UFSC). The thermostatic water bath provides water at the desired test temperature. The pump and the valve are used to control the mass flow rate, which is measured by a Coriolis mass flow meter. Water enters the lowest level of the PVT heat exchanger and comes out at the highest level. The slope of PVT heat exchanger (ϕ angle in Figure 2) can be adjusted but in these tests was kept constant at 32°.



Fig. 2: Schematic illustration of the indoor test bench

Figure 3 presents a cross section of the PVT heat exchanger test bench. The electric heaters apply a heat flux over the aluminum plate, this flux is controlled by a DC power supply and is varied between 200 W m⁻² and 800 W m⁻². The aluminum plate pretends to be the PV module and the heat exchanger under its surface fulfills the function of removing heat and delivers heat to water inside the corrugated PP sheet channels. To assess the heat exchanger effectiveness, not only the heat flux applied may be varied, but the water inlet temperature too. Three different water temperatures entering in heat exchanger channels were tested: 30 °C, 45 °C and 60 °C. Moreover, tests are carried out with and without the thermal insulation under the bottom heat exchanger surface.

Applications that demand water at temperatures higher than 40 °C, like domestic hot water heating, the bottom insulation must be used, although the PV module efficiency may be reduced. For applications that demand low

water temperatures, like pool heating, the bottom thermal insulation can be dismissed, and the PV module efficiency can be increased due to the cooling effect, depending on the water inlet temperature.



Fig. 3: PVT heat exchanger test bench cross section view

Figure 4 shows some details of the PVT test bench. Figure 4a shows the electric resistance installed on the top of the aluminum plate. Nickel chromium resistance strips were used with 22 mm between them, providing a uniform heat flux set at the bottom of the aluminum plate. Four aluminum plates of 300 mm wide and 450 mm long were used. All the nickel chromium strips are connected in series with a total electric resistance of 18 Ω . Figure 4b shows the aluminum plate bottom surface where the heat exchanger is installed. Figure 4c presents the test bench mounted with the heat exchanger installed.



Fig. 4: PVT heat exchanger test bench aluminum plate with nickel chromium resistances (a), aluminum plate with uniform heat flux (b) and heat exchanger without bottom insulation (c)

The heat exchanger experimental results were used to validate a numerical model developed in the EES software. The EES algorithm is the one-dimensional heat exchanger energy balance discretization in steady state. The set of equations that compound the heat exchanger energy balance come from the energy balance between the nodes shown in Figure 5a. Figure 5b presents the correspondent thermal resistance circuit which connects the temperature nodes and energy fluxes.

The resistance between nodes 4 and 3 is the thermal contact resistance between the heat exchanger and the aluminum plate. This resistance indicates the quality of the heat exchanger fasten method and has a direct influence on the system performance. The vertical walls of the heat exchanger were considered adiabatic, once there are no temperature gradients in the horizontal direction. The heat flux from node 2 to 8 was considered by conduction through the PP vertical wall and by convection with the water (node 1). Radiation heat transfer occurs from surface 9 to the environment at ambient temperature. The radiation heat transfer was only considered for the



case of the system operating without bottom thermal insulation.

Fig. 5: Node temperatures in the PVT heat exchanger test bench cross section view (a) and in thermal resistance circuit (b)

The heat exchanger width is 300 mm and the length is 1800 mm, with a total area of 0.54 m². The proposed heat exchanger used in the indoor test bench is composed of 44 rectangular channels with a hydraulic diameter equal to 4.24 mm. The mass flow rate was kept constant at 20 kg/h at every test and the ambient temperature near 20 °C. The input data for the model is the ambient temperature, water temperature and electric heat flux at node 5, as well as the components properties and dimensions, shown at Table 1.

Quantity	Value
Polypropylene thermal conductivity	0.21 W m ⁻¹ K ⁻¹
Polypropylene emissivity	0.95
Insulation thermal conductivity	0.035 W m ⁻¹ K ⁻¹
Aluminum thermal conductivity	240 W m ⁻¹ K ⁻¹
Polypropylene thickness (nodes 3 to 4; 8 to 9)	0.8 mm
Insulation thickness	50 mm
Aluminum plate thickness	15.88 mm
Wood thickness	25 mm
Bottom insulation thickness	30 mm
Heat exchanger width	300 mm
Heat exchanger length	1800 mm
Number of channels	44

Tab. 1: Properties and dimensions

For determination of convection losses, it is important to define the convective heat transfer coefficient h. According to Duffie and Beckman (2006), the h acting on test bench upper and bottom surface (h_{1011}) is a combination of forced and natural convections:

$$h_{1011} = (h_{1011,nat}^{3} + h_{1011,forced}^{3})^{1/3}$$
(eq. 1)
$$h_{1011,nat} = 1.78 (T_{10} - T_{11})^{1/3}$$
(eq. 2)

 $h_{1011,forced} = 2.8 + 3u_w$ (eq. 3)

Where $h_{1011,nat}$ is the natural convection heat transfer coefficient, $h_{1011,forced}$ is the forced convection heat transfer coefficient, that is a linear function of the wind speed u_w , T_4 and T_{11} are the average surface and ambient temperatures, respectively. Besides, the inner channel convection coefficient (h_{28}) was calculated using a constant Nusselt number of 3.73, which is considered for rectangular tubes with laminar flow and nonuniform heat flux.

Figure 6a presents the PV module cross section with the heat exchanger installed and Figure 6b represents the heat transfer thermal circuit. This model considers that the solar radiation, *G*, reaches the surface 4 where PV cells are located, and it is converted into electrical and thermal energy. Surface 4 transfers the heat excess by radiation and conduction through the glass and the heat exchanger. The considered PV module on the simulations has a nominal PV efficiency (η_{OPV}) of 0.1811 and a power temperature coefficient of -0.37% K⁻¹. The electricity produced by the PV on the simulations depends on *G*, PV efficiency and *T*₄.



Fig. 6: Node temperatures in the PVT heat exchanger test bench cross section view (a) and in thermal resistance circuit (b)

The PV glass properties are transmittance-absorptance product, $\tau \alpha$, of 0.90, thermal conductivity, k_{glass} , of 1.2 W m⁻¹ K⁻¹ and a thickness of 3.2 mm. The solar cells emissivity was considered 0.95. The radiation heat transfer from surface 4 was considered as exchanges with sky in an effective sky temperature 5 K less than the ambient temperature. The PV module without the heat exchanger installed on its rear surface was also simulated in the same way to obtain its electric power generation and operation temperatures to compare with the simulated PVT results.

3. Results

Figure 7 shows the comparison of the experimental and calculated results for the nodes temperatures 4, 5, 7 and 9, where thermocouples were installed. These node temperatures represent top and bottom aluminum plate surfaces and top and bottom surfaces that are exposed to forced convection induced by wind speed. When the node temperature values were plotted in Figure 7, it was possible to fit them and find out the thermal contact resistance that minimizes the experimental and calculated temperatures. The obtained value for the contact resistance was $0.008 \text{ m}^2 \text{ K W}^{-1}$. This result will be employed in subsequent simulations in EES.



Fig. 7: Measured and calculated temperatures

Figure 8 presents a comparison between measured and calculated heat fluxes absorbed by the water. The error bars indicate the expanded uncertainty for the measured value, which is dependent on the temperature measurement uncertainty of 1% and the mass flow rate measurement uncertainty of 1%. It can be seen that almost all the experimental points in Figure 8 match the calculated ones considering its uncertainty interval. The negative values in Figure 8 represent the tests at high temperature in which the fluid loses more heat to the ambient than it gains from the electric resistance.



Fig. 8: Measured and calculated heat fluxes transferred to the water inside the heat exchanger

During experimental tests, the wind speed ranged from 0 m s⁻¹ to 2 m s⁻¹, which applied in Equations 1 and 3 resulted in the values of the convection heat transfer coefficient from $3.71 \text{ W m}^{-2} \text{ K}^{-1}$ to $8.95 \text{ W m}^{-2} \text{ K}^{-1}$.

Figure 9 shows the effect of thermal insulation on the amount of heat absorbed by water in presence of wind speed. Without bottom insulation, as wind speed increases more heat is lost by convection and less is collected by water, thus diminishing the heat exchanger performance. Nevertheless, when thermal insulation is installed in the heat exchanger rear surface the wind speed has a smaller influence on water heat absorption. Furthermore, as the

water inlet temperature increases the heat exchanger performance decreases due to a minor capacity of the fluid to absorb heat. The simulations presented in Figure 9 consider a heat flux at surface 4 of 400 W m⁻².



Fig. 9: Influence of wind speed on water heat absorption

The Reynolds number inside the PP channels ranged from 35 to 55 and h_{28} ranged from 530 to 555 W m⁻² K⁻¹. The h_{28} was varied in simulations, but no significant influence on the results was observed.

With the thermal model validated by the test bench experimental results, the PVT model, presented in Figure 6, simulation results are now presented in some parametric analysis.

The electric power generation by the PV and PVT modules is presented in Figure 10. The PV generation is represented by the red curve. The PVT electric generation for three different fluid temperatures is represented by the black curves. The effect of PV efficiency improvement by using the heat exchanger is observed when water circulating inside the channels is at the lowest temperature considered, 25 °C, equal to the ambient temperature. On average, when water inlet temperature is equal to ambient temperature the PVT efficiency is 4% higher than PV efficiency achieving an efficiency improvement of 8% for maximum *G* level simulated. The wind speed in these simulations was maintained in 1 m s⁻¹. For PVT with water inlet temperature of 45 °C the efficiency is 1,5% lower than PV efficiency. When the water inlet temperature is 60 °C, PVT efficiency is 7% lower than the PV.



Fig. 10: Electric power generated for the PV only and PVTs with different water inlet temperatures

The solar cells temperatures (T_4) in the same cases of Figure 10 are represented in Figure 11. For water inlet temperatures of 45 °C and 60 °C, T_4 presents 51 °C and 63,5°C of maximum values, respectively. For water inlet temperature equal to 25 °C, T_4 is 29.4 °C reaching a maximum of 34,2 °C when *G* is 1000 W m⁻².



Fig. 11: Average cell temperature, T4, of the PV and PVT with different water inlet temperatures

Figure 12 presents the thermal power generation of the PVT operating with different water inlet temperatures, without and with bottom thermal insulation. For the temperature of 25 °C, the PVT thermal generation in both cases are the same with a thermal efficiency in the range of 38% and 60% corresponding to a solar radiation of 100 W m⁻² e 1000 W m⁻². As expected, the thermal generation decreases with the increase of the fluid temperature. For temperatures higher than 45 °C, when the PVT panel is operating under *G* levels of 700 W m⁻² the heat losses are higher than the heat gained by water.



Fig. 12: PVT thermal energy generation when water inlet temperature and use of insulation change

Figure 13 presents the influence of thermal contact resistance on the PVT generation and on T_4 . In this simulation, the solar irradiance was defined as 800 W m⁻², ambient temperature as 25 °C, wind speed as 1 m s⁻¹ and water inlet temperature as 45 °C. Black curves depict PVT with bottom thermal insulation and red curves, PVT without thermal insulation. The blue line represents the value of 0.008 m² K W⁻¹ for the thermal contact resistance obtained experimentally. The thermal and electrical energy generation deteriorates with the increase of the average solar

cell temperature. For contact resistances lower than 0.003 m² K W⁻¹, the PVT performance is almost constant. Above this value, the cell temperature starts to increase and it is most accentuated between 0.01 m² K W⁻¹ and 0.1 m² K W⁻¹. The obtained value of 0.008 m² K W⁻¹ can be considered at the limit of a region in which both drop in the solar cell temperatures and the thermal and electrical performances can be considered negligible, i.e., they are independent of the contact resistance.



Fig. 13: Contact resistance influence on the electric power generation, thermal energy generation and average solar cells temperature.

4. Conclusions

The present paper showed a new concept of heat exchanger made of corrugated PP to be used in common PV panels, converting them into hybrid solar collectors. This heat exchanger presents simple manufacture and installation as well low final cost. Both in experimental and simulations, water circulates inside multiple channels of the heat exchanger with the main objective to remove heat from the hot surface passing it to the water. The heat removed decreases the PV module operating temperature maintaining it in values closer to water inlet temperature, increasing up to 8% PV efficiency.

The experimental tests were carried out utilizing the indoor PVT heat exchanger test bench. This test bench has components that control water mass flow rate, water inlet temperature and heat flux applied. Nonetheless, just the last two were varied in a specific range to assess the polymeric heat exchanger performance.

After carrying out a combination of experimental tests using different heat fluxes and water inlet temperatures, the thermal contact resistance of 0.008 m^2 K W⁻¹ was found out. This result was utilized in simulations encompassing the PVT heat exchanger test bench energy balance. These simulations showed that the thermal resistance circuit can estimate the heat flux absorbed by water circulating inside the PP heat exchanger. The difference between measured and calculated heat fluxes were on average 12% and 8% for experimental configurations without and with bottom thermal insulation, respectively.

With the simulation model validated with the experimental results, a PVT was simulated in a parametric analysis. It was shown that the fluid temperature circulating through the PVT has a major influence on the solar cell temperature. If water is at high inlet temperature about 60 °C, the electricity generation is decreased due to the PV conversion efficiency losses of 7%, on average. However, if water is entering at a lower temperature than that or near the ambient temperature, the electrical efficiency is increased 4%, on average.

The installation of thermal insulation causes a considerable reduction in the amount of heat lost to the environment by convection, then the thermal insulation decreases significantly the influence of wind speed in heat loss and improves the amount of heat absorbed by water. Without bottom thermal insulation, as wind speed increases, the heat exchanger performance decreases significantly. The use of the bottom thermal insulation is essential for domestic hot water applications, where the temperature difference between the desired water and ambient temperatures are usually above 20 °C. For applications at lower temperatures, like pool heating, the bottom insulation can be dismissed.

The influence on the thermal contact resistance was analyzed and the obtained value of 0.008 m² K W⁻¹ was considered appropriate for a good thermal and electric generation efficiency.

In future works, the authors will carry out tests using an outdoor PVT test bench, where the PP heat exchanger will be submitted to real weather conditions and its ability to heat water for domestic hot water use and for pool heating will be checked. The heat exchanger performance analysis will be expanded to annual simulations in different regions to assess the economic viability of the proposed heat exchanger.

5. Acknowledgments

This work was developed in R&D Project PD 00403 0049/2020 funded by the Research and Development Program of the National Agency of Electrical Energy (ANEEL) and Engie Brasil Energia S.A. The authors are grateful to the funders ANEEL and Engie and to the LEPTEN laboratory of the Federal University of Santa Catarina (UFSC), the Graduate Program in Mechanical engineering (POSMEC), Advanced Institute of Technology and Innovation (IATI) and Soluz Energia.

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Numerical Simulation of a cost efficient novel CPVT solar collector

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Abstract

In this work, the simulation of a Concentrated PhotoVoltaic Thermal (CPVT) solar collector system has been done by means of Finite Volume Method. The system consists of a parabolic collector, which concentrates solar irradiance onto solar cells, which are refrigerated attaching them to a pipe which contains water. At the same time, this water is warmed up. Numerical results are compared with experimental data both obtained within the current eranet project for the Economic COgeneration by Efficiently COncentrated SUNlight (ECOSUN). The idea of this project is to study how to take advantage of the residual heat produced by the photovoltaic elements. Warming up water is proposed as a possibility, due to the synergy obtained because water refrigerates the whole system. First numerical results show a reasonable agreement against experimental data. The CPVT model of this project is oriented to optimize the design for solar cooling applications. Finally, new pipe geometries including fines are purposed in order to increase the thermal heat exchange between the CPVT solar collector and the water.

Keywords: parabolic collector, solar energy, solar power, solar cell, FVM, CPVT.

1. Introduction

Solar cell technology combines knowledge of different areas, such as physic of materials and thermal engineering. One powerful tool that allows us to obtain better analysis of a solar cell system and help us in the optimizing process is Computational Fluid Dynamics (CFD) (Guadamund, et al.). This field of knowledge takes charge solving (numerically) the equations that govern the physics involved in the physics of fluids and heat and mass transfer, allowing us to simulate different configurations of physical systems, such as the ones involving solar energy.

The purpose of this project is focused on concentrated photovoltaic thermal collector (CPVT), which concentrates solar irradiance onto a row of photovoltaic solar cells (Sharaf and Orhan). At the same time, these solar cells must be refrigerated in order to work optimally. This could be done, for instance, attaching these solar cells to a pipe which contains some fluid (water in our case). Furthermore, this residual heat could be used to warm up this fluid. ECOSun project has as main objective of cost reduction of electricity and heat co-generation via a Concentrated Photovoltaic/Thermal (CPV-T) system by applying low-cost materials and advanced industrial manufacturing methods. In the CPV-T system, the solar radiation is captured in parabolic through concentrator based on a novel support structure fabricated by injection moulding and focused on a Co-Generation Absorber Module (CAM), where special c-SiPV-cells are operated under concentration. One of the subtasks of the project has been to simulate properly the whole CPVT system, comparing our results against the results obtained experimentally. Different configurations of inflow water will be taken into account, using a closed system with a glass envelope and low-pressure air. The whole CPVT system can be attached to absorption machines in order to take advantage of the residual heat (Castro et al.).

By means of experimental data, the CFD analysis is able to model all heat transfer processes reproducing the whole phenomena not only for validation purposes by means of experimental data comparison and physical models' calibrations, but also to simulate different system conditions, avoiding the necessity of repeating an experiment for such conditions. In this regard, we can obtain new results for different materials or configurations of the pipe, including shape and the possibility of having fins.

2. Numerical Model and Implementation

The CPVT solar cell system, illustrated in Figure 1, can be physically decomposed into three parts: solid regions, fluid domains and coupling interfaces. In the following list, the equations to be solved in each region are shown.



Fig. 1: CPVT cross section configuration (left); CPVT configuration front of parabolic collector (collector not included)

Solid elements: energy equation conservation, (note that for this case, the velocities are equal to 0).

$$\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla \mathbf{T} = \frac{k}{\rho c_p} \nabla^2 \boldsymbol{T} + \frac{J}{\rho c_p}, \qquad (\text{eq. 1})$$

where T is the temperature, **u** is the velocity (**u**=0 for solid elements), k is the thermal conductivity, ρ is the density, c_p is the heat capacity and J is the source term.

• Fluid elements: (Eq.1) + Incompressible Navier-Stokes equations with buoyancy term (Boussinesq approximation):

$$\nabla \cdot \boldsymbol{u} = \boldsymbol{0}, \qquad (\text{eq. 2})$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = -\frac{1}{\rho} \nabla (p - \rho \boldsymbol{g} \cdot \boldsymbol{z}) + \nu \nabla^2 \boldsymbol{u} - \boldsymbol{g} \beta (T - T_0), \quad (\text{eq. 3})$$

where **u** is the velocity, p is the pressure, ρ is the density, v is the kinematic viscosity, **g** is the gravity constant, β is the thermal expansion coefficient, and T is the temperature.

- Coupling interfaces (solid-solid and fluid-solid):
 - Heat flux exiting one domain enters the other: Q1 = -Q2.
 - Same temperature at the interface: $T_1 = T_2$.

The heat flux is computed taking into account convective and radiative terms. Natural convection is found in the surrounding air, while forced convection can be found between the fluid and the pipe. The radiation model used is the Finite Volume Discrete Ordinates Method, which solves the RTE (Radiative Transfer Equation):

$$\hat{\boldsymbol{s}} \cdot \nabla l(\boldsymbol{r}, \hat{\boldsymbol{s}}) = \kappa l_b + (\kappa + \sigma_s) l,$$
 (eq. 4)

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applying a finite volume method (Colomer, 2006; Wang, 2020). In the previous equation, the intensity radiation field I is solved, which is defined as the energy due to radiation, propagating along a given direction \hat{s} , that crosses a unit area normal to \hat{s} , per unit area, unit solid angle around \hat{s} , unit wavelength and time. The absorption coefficient κ and the scattering coefficient σ_s model the medium behavior.

Finally, the radiation coming from the parabolic collector is assumed as a radiative boundary condition computed as (Zarza, 2015):

$$q = \frac{W_{par}}{W_{pV}} G_b \eta_{opt}, \qquad (\text{eq. 5})$$

where W_{par} is the aperture width of the parabola, W_{pV} is the height of the solar cells, G_b is the direct solar irradiance and η_{opt} is the optical efficiency of the parabola.

In order to perform simulations of the experiments, a software that has allowed to simulate conjugate heat transfer equations has been required. Furthermore, radiation must also be solved. OpenFOAM code (OF) has been chosen to do this particular task. The solver selected from OF library has been "chtMultiRegionFoam". This is a transient solver capable to deal with conjugate heat transfer between solid and fluid regions. Besides, radiation can be added to the solver too. Regarding radiation models, OF code has three integrated models: surface-to-surface model (or view factors model), P1 and fvDOM. Last one has been chosen for the sake of being the more precise model.



3. CPVT Simulation

Fig. 2: CPVT solar collector experimental configuration scheme (collector not included) (Felsberger, et. al. 2020)

As we can see in Figure 2 from a general point view, important components of the system to take into account are the following ones: i) an absorber pipe; ii) a printed circuit board (PCB) which have the solar cells attached; and iii) a piece which connects the PCB with the pipe and an envelope glass to isolate the system. Furthermore, a parabolic solar collector is used to concentrate solar power onto the solar cells. Finally, an envelope glass (100mm diameter) is used to cover our system with a low-pressure air.

Radiation is coming from the parabolic collector and enters in the system, while PCB is heating up, water is flowing from left to right absorbing heat and cooling the solar cells.

3.1 Numerical verification and detailed validation

The model has been numerically verified and experimentally validated using data coming from EcoSUN experimental test cases under lab tests conditions (Felsberger, et. al. 2020; Buchroithner, et al.). These experiments consisted of a single CPV cell which received controlled radiation guided by a tunnel. This cell was attached to a pipe using a piece of copper. The pipe contained water flowing which refrigerated our system. Figure 3 shows a schematic picture of the experiment. A temperature sensor was located behind the CPV cell.



Fig. 3: CPVT single solar collector experimental configuration (Felsberger, et al. 2020; Buchroithner, et al.).

The main purpose of this model was to reproduce properly the temperature reached by the system in the steady state. In figure 4, the temperature obtained numerically with our model is shown, along with the steady state temperatures obtained in the experiments. In both cases, numerically and experimentally, temperatures were between 33-34°C in the sensors. Numerical results on outlet fluid water temperature and different solid temperature points along the conduct present a very good agreement with an error lower than 3% in all cases. Once our model has been tested, we can advance to the next step: the simulation of a full CPVT solar collector. Even though we have tested the physical model, its robustness will be tested again against experimental data of the CPVT solar collector experiment.

Temperature of the sensors and water



Fig. 4: Temperature obtained at temperature sensors. Water input temperature is 20.0°C. Slashed lines represent the steady state temperature found in the experiments.

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3.2 Numerical test cases under real working conditions

Different tests have been done within this configuration in order to obtain experimental data (Felsberger, et. al. 2021). The main test consisted of three experiments with different irradiances (DNI) and different heat transfer fluid (HTF) temperature. These experiments were carried out with a glass envelope of 3mm thickness, an HTF flow rate about 11 L/min.

The first one had an HTF temperature of 17°C and a DNI of 780 W/m2, the second one an HTF of 65°C and a DNI of 750 W/m2 and the last one had an HTF of 90°C and a DNI of 650 W/m2. Again, the objective is to reproduce properly the steady state temperature reached by our system.

The chosen mesh contains 640.000 control volumes, and it has been refined in areas where the heat transfer is intense. The numerical simulation results for the temperature have been compared to the experimental ones to check their precision. Thus, the value of the temperature has been extracted in the same location as the temperature sensors are located.

Figures 5, 6 and 7 show an overview of the temperature reached by our system in a steady state, such as the temperature measured numerically at the location of the sensors. All the results have a reliable agreement with the experimental ones. The numerical temperature curves display the same behaviour as the experimental ones, and the temperature of the sensors are in good agreement with the experiments:





Fig. 5: HTF 17°C case. (Top) Steady state temperature profile behind the PCB. (Bottom) Temperature of the sensors over time.



Fig. 6: HTF 65°C case. (Top) Steady state temperature profile behind the PCB. (Bottom) Temperature of the sensors over time.



Fig. 7: HTF 90°C case. (Top) Steady state temperature profile behind the PCB. (Bottom) Temperature of the sensors over time.

A short orange region can be found at the HTF entry of each solid region. This effect is caused by the heat transfer from the pipe to the PCB, and it was also observed by the experiments. Radiation also warms up the solid pipe, and part of this heat is transferred to the PCB.

Tab. 1: Comparison between experimental data and numerical results (steady-state). The temperatures shown in the table are the
maximum temperatures measured by the sensors.

	Experimental data	Numerical results
HTF 17°C	33°C	32.6°C
HTF 65°C	75°C	77°C
HTF 90°C	98.4°C	98.9°C

As we can see in the table 1, a very good agreement is found between experimental sensor temperature and the numerical one. Assuming the experimental data is correct, the maximum error (2.7%) is found in the HTF 65°C. Thus, the model is showing robustness not also under lab conditions but also under real conditions.

4. Towards new geometries

Once the model has been proved to produce good results, this model is going to be used to try new pipe geometries. The main idea of changing the geometry of the pipe (or adding fines) is to increase the heat transfer rate from the pipe to the fluid. Thus, the PCB is reducing its temperature while the fluid is absorbing more heat. Again, the code used to perform the simulations is going to be OpenFOAM. The two pipe designs we are going to test consists of a semicircular pipe with fins. These models and the meshes are described in figures 8 and 9:



Fig. 9: Mesh used to solve the circular Fin-Heatsink case.

We have results for the previous cases (HTF 17°C, HTF 65°C and HTF 90°C). These results will allow us to compare if these new designs could be more optimum than the previous one. Table 2 shows us a comparison between the temperature measured by the sensors of the previous case (circular pipe) and these new designs:

	Base case	Fin heatsink case	Circular fin heatsink case
HTF 17°C	32.6°C	25°C	26.5°C
HTF 65°C	77°C	72.5°C	73.9°C
HTF 90°C	98.9°C	94.6°C	95°C

 Tab. 2: Comparison between numerical results obtained for both cases. The temperatures shown in the table are the maximum temperatures measured by the sensors.

A decrease of around 4.3° C – 7.6°C in the maximum PCB sensor temperature can be seen using a fin heatsink pipe. Table 3 show the average temperature of the back part of the PCB:

 Tab. 3: Comparison between numerical results obtained for both cases. The temperatures shown in the table are the average temperature of the back part of the PCB.

	Base case	Fin heatsink case	Circular fin heatsink case
HTF 17°C	31.3°C	23.9°C	24.3°C
HTF 65°C	76.5°C	71.4°C	71.8°C
HTF 90°C	97.8°C	93.8°C	93.9°C

We can also observe that the fin heatsink seems to work slightly better than the circular fin heatsink within this fluid regime. The explanation for this phenomenon can be explained observing that the maximum heat transfer rate is happening in the fluid region near the PCB, causing the fin-solid part which is further of the PCB to be almost at the fluid temperature. These are good news due to the fact that circular fins are more difficult to manufacture than regular ones (and they are also more expensive).

Furthermore, as the HTF temperature is increased, the maximum PCB temperature reduction is decreased. However, it is still a significant temperature reduction.

In order to quantify the efficiency of the cooling part of the CPVT solar cell, we can define the following quantity:

$$U = \frac{G_b}{\Delta T}, \qquad (\text{eq. 6})$$

$$\Delta T = \frac{(T_{pV} - T_{in}) - (T_{pV} - T_{out})}{ln \frac{(T_{pV} - T_{in})}{(T_{pV} - T_{out})}},$$
 (eq. 7)

where T_{pV} is the average temperature at the back part of the PCB, T_{in} is the temperature of the flow at the entrance of the PCB and T_{out} is the temperature of the flow at the exit of the PCB. Observe that this coefficient U provides information about the efficiency of the heat exchange between the PCB and the water flow: the higher the coefficient, the more efficient is the heat exchange, hence, the cooling process.

	U HTF 17°C	U HTF 65°C	U HTF 90°C	Pressure drop per meter
Base case	63.3	73.7	77.8	16.4
Fin heatsink case	162.0	152.4	154.5	73.1
Circular fin heatsink case	155.4	146.0	148.7	96.2

Tab. 4: Heat transfer coefficient U and pressure drop per meter obtained for the different cases and geometries.

As we can see in table 4, the heat transfer coefficient obtained in the fin heatsink cases is almost 2.5 times the heat transfer coefficient of the base case. Furthermore, we can observe that the heat transfer coefficient seems to increase with temperature while this is not happening for the fin heatsink cases. This could explain why the difference of average temperatures seem to decrease while the HTF temperature is increasing. Furthermore, the pressure drop per meter of the fin heatsink case is slightly lower than for the circular fin heatsink case. All these results seem to point out that the fin heatsink will perform better than the circular fin heatsink.

5. Conclusions

A whole and detailed numerical model for CPVT systems has been numerical developed, verified and experimentally tested under different tests conditions. The numerical tool is going to demonstrate an excellent capability of prediction the thermal behaviour of the system, but also as a design tool to develop an optimum configuration for specific solar cooling application. Besides, deep studies must be done in order to optimize the heat absorption. Within this work line, an optimization process to find the optimal number and distances between fins must be carried out.

6. Acknowledgments

This project has received funding from SOLAR-ERA.NET Cofund 2 joint call undertaking under the European Union's Horizon 2020 research and innovation programme.

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A Detailed Investigation on the Convective Heat Transfer Inside the Enclosed Cavity of Insulated Glass Solar Thermal Flat-Plate Collectors

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Abstract

In the solar thermal industry, there is a trend towards large-scale solar district heating plants. However, building large plants can also lead to problematic fluctuations in demand for collector manufacturers. To tackle this issue, an innovative concept was introduced which adapts the collector design to production techniques of the insulating glass industry. The insulated glass solar thermal flat-plate collector (IGFPC) raises new questions regarding efficiency and convective heat losses. The objective of this research was to determine the natural convection characteristics of this collector design. A review of Nusselt number correlations revealed, that the gas cavity of the collector can be partially described using equations from literature. As these equations do not consider both large aspect ratios and higher temperature levels, a computational fluid dynamics simulation was performed. The results show that convective heat transfer inside IGFPCs occurs predominantly in front of the absorber, whereas inside the rear cavity the flow patterns are subcritical, resulting in smaller convective losses. As a consequence, the absorber of this collector should be positioned asymmetrically in order to minimize its convective losses. A new set of Nusselt correlations has been derived to express the heat transfer characteristics for typical operating ranges of IGFPCs and various inclination angles.

Keywords: solar thermal collector, flat-plate collector, insulated glass, convective heat losses, natural convection, computational fluid dynamics, solar district heating, Nusselt correlations, Rayleigh number, inclination angle

1. Introduction

As global temperature rises, the need for achieving the climate targets within all sectors of our society is a must. It's noted that most of the carbon dioxide emissions in the northern hemisphere are related to electricity and heating processes (World Resources Institute, 2019) where specifically, heating has the biggest share of overall energy consumption in European households (Eurostat, 2018). Many leading countries have proven that large-scale district heating plants based on solar thermal resources can be operated both efficiently and profitable (Tschopp et al., 2020). However, large solar thermal projects may cause high fluctuations in demand, resulting in financial challenges for collector manufacturers (REN21 Secretariat, 2020).

A solution to tackle such a problem is to redesign the solar thermal flat-plate collectors (FPCs) in a way that can lower the manufacturing cost without losing too much of overall efficiency. One approach to achieve this, is the concept of insulated glass solar thermal flat-plate collectors (IGFPCs) which were studied by different researchers in the last years (Giovannetti et al., 2014; Giovannetti and Kirchner, 2015; Leibbrandt et al., 2017; Leibbrandt and Schabbach, 2020; Leibbrandt et al., 2022). What sets this collector apart is the idea of fixing the absorber between two glass panels, as seen in Fig. 1. Using a manufacturing technique similar to insulated double-glazed units allows for the injection of noble gas into the collector cavity, which reduces thermal losses. A polymeric adhesive at the glass edges ensures both the hermetic sealing of the gas cavity and the mechanical stability of the assembly.

Convective losses through the cavity between the glazing and the absorber represent the dominant part of heat losses in flat-plate collectors. Hence, the phenomenon is discussed as early as the 1950s (de Graaf, J. G. A. and van der Held, 1953). The lack of insulation material at the back side IGFPC increases the share of

convective and radiative losses. Throughout the years, many researchers studied factors which affect the thermal energy transfer through the cavity as glazing type, cavity medium and aspect ratio. Moreover, many researchers developed correlations that determine the convective losses between absorber and the frontside glazing of an FPC.



Fig. 1: Schematic and simplified structure of an IGFPC consisting of two glass covers, an absorber plate and an edge seal compound. Inlet and outlet ports are not drawn for reasons of simplicity.

In order to fully assess the potential of IGFPCs, an investigation on the convective heat losses of IGFPCs with regard to both cavities was made in this present study. The losses in the rear cavity were not investigated with regard to IGFPCs. The presented article focuses on the convective heat losses of such collectors by analyzing both front and rear cavities. The objective of this research is to determine the convective heat transfer characteristics of such a configuration by reviewing former applicable findings and verifying the results with numerical flow simulations.

2. Methodology

2.1 Review of empirical Nusselt correlations

As shown in an earlier investigation (Summ et al., 2020), the front and back side of the IGFPC may be considered as two separated cavities. Heat losses that occur at the side boundaries can be neglected. There are two arguments to justify this assumption. Firstly, the thickness of a large-area collector (LAC) is several orders of magnitude smaller than the collector length or width. Secondly, the material used in the edge seal compound of the IGFPC holds significantly lower thermal conductivity than the materials used in conventional collectors. Condensing the losses in such a way allows for the application of well-known equations in order to describe the convective heat losses of the IGFPC.

In order to give an overview of the existing methods for calculating the convective heat losses of IGFPCs, an investigation on empirical expressions describing rectangular cavities was conducted (cf. chapter 3.1). Natural convective heat transfer is typically quantified in terms of Nusselt number (Nu) which significantly depends on Rayleigh number (Ra) and the inclination angle of the cavity (φ). These expressions (also called correlations), were later (cf. chapter 3.3) used to compute the heat transfer coefficient (h) by applying the definition of Nusselt number:

$$h = \frac{Nu(Ra, \varphi) k}{W}$$
 (eq. 1) k: thermal conductivity of the gas inside the cavity

2.2. Computational fluid dynamics simulation setup

The correlations given in the literature cannot be applied for the entire spectrum of geometrical and operating properties that are relevant for the design of IGFPCs. Additionally, since many correlations exist, it is worth finding the most accurate one which can describe the convective losses for this particular collector concept. In this context, computational fluid dynamics (CFD) simulations of the described cavities were performed. Typical boundary conditions for LACs used for district heating applications were incorporated. The CFD

model was compared and validated with the empirical results of other authors (cf. chapter 2.3 / 3.2).

As described in chapter 1, the cavity is modelled as a cuboid and has the dimensions of $L \times W \times D$ (length, width, and depth). The model uses a symmetry boundary condition to the cross-section plane (cf. Fig. 1) to reduce the computational effort, resulting in a fluid domain with the size $L \times W \times \frac{D}{2}$.

To provide a structured mesh and therefore numerical stability as well as computational speed, a mesh with hexagonal elements was created. Size functions have been used to create refinements at the walls and to resolve boundary layer effects. The number of edge divisions was varied for each side of the geometry. The selected parameters are listed in Tab. 3. Consequently, a cell count of roughly two million elements was set. The mesh needed adaptation after validating the model, as the aspect ratio (AR = L/W) was up to 10 times higher for the parametric study. The width and length of the cavity were changed and hence, the mesh refinements too.

The CFD simulation was performed using ANSYS Fluent 2020R2 software (ANSYS, Inc., 2020). A steadystate, pressure-based finite volume approach was selected to solve the Navier-Stokes equations numerically. The Reynolds stress turbulence model was used to account for high Rayleigh numbers, turbulent flow regimes and turbulent boundary layer effects.

The physics of natural convection require the gas properties to be temperature dependent. Therefore, the ideal gas law and kinetic theory were used to compute density, thermal conductivity, viscosity, and heat capacity of the gas. The parameters for the used gases Air and Argon are listed in Tab. 4. In this study, the CFD computation was validated using Air as a cavity gas. However, an analytical computation accounting for Argon was conducted as well (cf. chapter 3.3).

The boundary conditions were applied to four regions: a constant temperature at the surfaces representing the absorber and the front/back glass cover; an adiabatic condition at the side walls; a symmetry condition at the cross-section plane. The inclination was varied by changing the components of the gravity vector using the following expressions: $g_x = g \sin \varphi$ and $g_z = -g \cos \varphi$, where $g = 9.81 \text{ m s}^{-2}$.

Output parameters from the Fluent model were the heat flow rate \dot{Q} , Rayleigh and Nusselt numbers which were computed using their common definitions:

$$Nu = \frac{hW}{k} = \frac{QW}{kL\frac{D}{2}\Delta T} \quad (eq. 2) \qquad Ra = \frac{g\Delta TW^3\rho c_p}{\nu T_{gas}k} \quad (eq. 3)$$

 ΔT : temperature difference ρ : mass density c_p : heat capacity ν : kinematic viscosity T_{gas} : gas temperature

2.3 Validation of the CFD model with empirical findings

The collected equations from the literature have been used for validating the numerical model. Not all equations are valid for the entire range of Ra and φ . However, the collection of correlations covers the range for this study to a high degree. The parameters were selected in such a way that most of the equations could be used to compute values for Nu.

Thus, the computation was performed for the inclination angles $\varphi = \{0, 15, 30, 45, 60\}^\circ$ as well as for Rayleigh numbers $Ra = \{10^3, 5 \times 10^3, 10^4, 5 \times 10^4, 10^5\}$. Several values for ΔT were selected in order to achieve the four stated levels of Ra and were respectively $\Delta T = \{0.571, 2.858, 5.717, 28.583, 57.165\}$ K. More details on the geometrical setup are described in Tab. 3. For validation, isothermal boundary conditions were used for the front cover and the absorber. To validate the model, the results from the correlations were then compared to the simulation outputs by means of Nu vs. Ra plots.

2.4 Parametric study using the CFD model

To analyze the collector characteristics, a parametric study was conducted. The width of the cavity (W) and the angle (φ) were used as geometric parameters, whereas the temperature difference (ΔT) was varied as a parameter related to the operating point of the collector. A constant length of L = 2.5 m and depth D = 1.5 m was implemented, accounting for the larger sizes of IGFPCs as compared to the geometry for validation.

As described in chapter 2.1, the front and back side of the absorber were computed separately. Eismann (2015) found in his investigation on the convective losses of FPCs, that the inhomogeneous temperature distribution

across the absorber is relevant for computing the thermal losses. Therefore, in this study the boundary conditions of the absorber were set to be non-isothermal as well. A negative linear temperature gradient along the absorber plate was applied to this boundary in order to account for an inhomogeneous temperature field. At both ends of the absorber, the temperature is set to be the inlet and outlet temperature of the heat transfer fluid¹. The side walls of the geometry were defined as adiabatic and the boundary for the glass cover was defined as isothermal.

For the parametric study, inlet, outlet, and glass temperature were varied. This leads to a set of different Rayleigh numbers. During operation, solar thermal collectors can have various temperature distributions. To cover a realistic range of operation modes, four sets of parameters have been defined. Tab. 1 shows the four parameter sets that were used for the CFD computations. Additionally, the inclination angle (φ), and cavity width (W) were altered as: $\varphi = \{10, 40, 70, 110, 140, 170\}^{\circ}$ and $W = \{5, 16.25, 27.5, 38.75, 50\}$ mm. This results in a total number of 125 simulations for the parametric study. Here, φ and W were selected to cover a broad range of realistic operating and design characteristics. Linear spacing was used for W to have five equally spaced parameters between 5 mm and 50 mm.

3. Results and Discussion

3.1 Review of empirical approaches

The heat transfer across the gas layer of enclosed cavities has been studied very thoroughly. Researchers identified mathematical correlations for different physical boundary conditions such as temperature level, cavity dimensions or gas types. Within the presented study, a collection of correlations has been obtained describing the convective heat transfer across rectangular shaped enclosed cavities. Investigations that only covered low aspect ratios (< 8) or a Prandtl number (Pr) range for liquids or other types of geometries have not been included in the collection. Tab. 2 shows the correlations as well as their specific validity range. Some of these equations can be applied to the back side of the collectors as well, such as the ones from Ayyaswamy and Catton (1973), Ozoe et al. (1975), and ElSherbiny (1996).

As this type of collector shall be used for district heating applications, these assumptions were made:

- The inlet temperature T_i of the collector ranges from 10 °C to 70 °C
- The outlet temperature T_o of the collector ranges from 20 °C to 120 °C
- The temperature spread $S = T_o T_i$ between inlet and outlet ranges from 0 K to 50 K
- The ambient temperature T_a ranges from -10 °C to 30 °C
- The inclination angle φ of the collector ranges from 10° to 70°
- The average collector temperature is $T_m = 0.5 (T_o + T_i)$
- The average glass cover temperature is $T_{gl} = 0.5 (T_m + T_a)$
- The average cavity gas temperature is $T_{gas} = 0.5 (T_m + T_{gl})$

These considerations given, the operating temperature difference $\Delta T_c = T_m - T_a$ for IGFPCs ranges between -15 K and 105 K. As the presented work is aimed in the convective losses only, the values $\Delta T_c < 0$ K were neglected. Hence, the front and back cover will have higher or equal temperatures than ambient. For a computation of the Rayleigh and Nusselt numbers, we define the temperature difference as $\Delta T = T_m - T_{gl}$. The aforementioned temperatures yield ΔT between 0 K and 52.2 K and average gas temperatures T_{gas} between 8.75 °C and 78.75 °C.

Within this study, the investigated IGFPC has a length of L = 2.5 m and a depth of D = 1.5 m. Since the cavity width W will affect Rayleigh number and therefore the heat losses, this parameter is an important design measure. It is assumed to vary from 5 mm to 50 mm both at the front and the back side of the absorber. The aspect ratio of the cavity AR will therefore range from 50 to 500. It has been shown by Inaba (1984), that for large aspect ratios the dependence of Nu to AR will become negligible. However, the existing correlations are

¹ In the model, no heat transfer fluid (HTF) is included. The temperature is referring to the HTF that would have effect on the absorber temperature during a real operation of the collector.

not depicted to have validity for such large aspect ratios (cf. Tab. 2). The frequently cited work from Hollands et al. (1976) is valid for $Ra \le 10^5$ and AR = 48. None of the applicable correlations from literature will exceed aspect ratios of 100. Considering all these assumptions and definitions, we obtain a Rayleigh number range as $Ra < 3.2 \times 10^5$ for this study.

Tab. 1: The selected set of parameters that were used for the parametric study

No.	T_i [°C]	$T_o [^\circ \mathrm{C}]$	$T_{gl} [^{\circ}\mathrm{C}]$	$\Delta T [K]$	<i>S</i> [K]	$\Delta T_c [K]$	$T_m [^\circ \mathrm{C}]$	T_{gas} [°C]
1	40	70	42.5	12.5	30	25	55	48.75
2	60	110	57.5	27.5	50	55	85	71.25
3	70	80	32.5	42.5	10	85	75	53.75
4	70	110	40.0	50.0	40	100	90	65.00

Reference	Nu-Ra-Correlation	φ in °	$Ra / Ra_{\varphi} / Gr$	AR
de Graaf, J. G. A. and van der Held, 1953	$Nu = C Gr^n$ Various values for C and n depending on φ and Gr	0, 20, 30, 45, 60, 70, 90	2×10^{3} < Gr < 2×10^{5}	18.8 34.1 62.3
Ayyaswamy and Catton, 1973	$Nu = Nu_{90^\circ} [\sin\varphi]^{0.25}$	70 <φ< 120	$Ra AR^3 \sin \varphi$ \gg 10^4	$AR \gg \cot \varphi$
Ozoe et al., 1975	$Nu = 0.109 Ra_{\varphi}^{-1/3}$	"small angles"	10^{3} < Ra < 10 ⁵	8.4 15.5
Hollands et al., 1976	$Nu = 1 + 1.44 \left[1 - \frac{1708}{Ra_{\varphi}} \right]^{+} \left[1 - \frac{1708 \left(\sin(1.8\varphi) \right)^{1.6}}{Ra_{\varphi}} \right] + \left[\left(\frac{Ra_{\varphi}}{5830} \right)^{1/3} - 1 \right]^{+}$	$\begin{array}{c} 0 \\ \leq \varphi \\ 60 \end{array}$	$0 \le Ra \le 10^5$	48
Buchberg et al., 1976	$\begin{aligned} Nu &= 1 + 1.446 \left[1 - \frac{1708}{Ra_{\varphi}} \right]^{+} & 1708 < Ra_{\varphi} < 5900 \\ Nu &= 0.229 Ra_{\varphi}^{0.252} & 5900 < Ra_{\varphi} < 9.2 \times 10^{4} \\ Nu &= 0.157 Ra_{\varphi}^{0.285} & 9.2 \times 10^{4} < Ra_{\varphi} < 10^{6} \end{aligned}$	$\begin{array}{c} 0 \\ \leq \varphi \\ 60 \end{array}$	$1708 < Ra_{\varphi} < 10^{6}$	_
Randall et al., 1979	$Nu = 0.118 \ Ra \cos \varphi - 4520.29$	$\begin{array}{c} 45\\ \leq \varphi \leq \\ 90 \end{array}$	2.8 × 10 ³ < Ra < 2.2 × 10 ⁵	9 – 36
Schinkel, 1980	$Nu = C Ra^{1/3} \qquad \begin{array}{l} \varphi = 0^{\circ} C = 0.080 \varphi = 10^{\circ} C = 0.079 \\ \varphi = 20^{\circ} C = 0.075 \varphi = 30^{\circ}, 40^{\circ}, 50^{\circ} C = 0.074 \\ \varphi = 60^{\circ} C = 0.072 \varphi = 70^{\circ} C = 0.069 \\ \varphi = 80^{\circ} C = 0.068 \varphi = 90^{\circ} C = 0.062 \end{array}$	$\begin{array}{c} 0 \\ \leq \varphi \\ 90 \end{array}$	10 ⁵ < <i>Ra</i> < 4 × 10 ⁶	6 – 27
Inaba, 1984	$ \begin{split} Nu &= 1 + 1.21 \left(1 - \frac{2500}{Ra_{\varphi}} \right) & 2.5 \times 10^3 < Ra_{\varphi} < 6 \times 10^3 \\ Nu &= 0.199 \; Ra_{\varphi}^{0.258} & 6 \times 10^3 < 8a_{\varphi} < 4 \times 10^5 \\ Nu &= 0.0785 \; Ra_{\varphi}^{0.330} & 4 \times 10^5 < Ra_{\varphi} < 1.2 \times 10^6 \\ Nu &= 0.271 \; AR^{-0.21} (Ra \sin \varphi)^{0.25} & 5 \times 10^3 < Ra \sin \varphi < 1.2 \times 10^6 \\ and \; 60 < \varphi \leq 120 \end{split} $	$0 \le \varphi \le 120$	2.5×10^{3} < <i>Ra</i> < 1.2×10^{6}	5 – 83
ElSherbiny, 1996	$Nu_{180} = [1 + (0.212 Ra^{0.136})^{11}]^{1/11}$ $Nu_{120} = [1 + (0.0566 Ra^{0.332})^{4.76}]^{1/4.76}$ $Nu = Nu_{180} + \frac{180 - \varphi}{60} (Nu_{120} - Nu_{180})$	$\begin{array}{c} 120 \\ \leq \varphi \leq \\ 180 \end{array}$	10 ² < Ra < 2 × 10 ⁶	20
Matuska and Zmrhal, 2009	$Nu = (0.1464 - 2.602 \times 10^{-4} \varphi - 2.046 \times 10^{-6} \varphi^2) Ra^{0.29}$	$\begin{array}{c} 0 \\ \leq \varphi \\ 90 \end{array}$	$10^4 \le Ra \le 2 \times 10^6$	_
Eismann, 2015	$Nu = 1 + Nu_1 + Nu_2$ $Nu_1 = 1.44 \left(1 - \frac{1708}{Ra + 1708 R_c}\right) \left[1 - (\sin(1.8 \varphi))^{1.6} \frac{1708}{Ra + 1708 R_c}\right]$ $Nu_2 = \left[\left(\frac{Ra + 5830 R_c}{5830}\right)^{0.39} - 1\right] (1 + C R_c)$	_	$ \begin{array}{c} 10^3 \\ \leq Ra \\ 10^6 \end{array} $	_

Tab. 2: Collection of Nusselt correlations from the literation
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¹ Superscript []⁺ indicates that only positive values will be counted as $[A]^+ = 0.5[abs(A) + A]$
IGFPCs are expected to work efficiently when Argon is filled in the enclosed cavity between the front and back glass pane. Due to its lower thermal conductivity, the gas causes lower convective heat losses compared to an air-filled cavity. Since the thermodynamic properties of Argon are different to the ones of Air, the resulting Rayleigh number for the same state of collector operation is higher. With respect to the values computed above, Ra is up to 3.70×10^4 higher when Argon is filled inside the cavity. This effect has to be accounted for when designing IGFPCs. Argon and Air have different Prandtl numbers. However, authors have found that Nusselt number is independent of Pr which is why most of the correlations do not account for Pr.

3.2 Validation results

The Nusselt-Rayleigh relation is shown in Fig. 2 for the five inclination angles 0° , 15° , 30° , 45° and 60° . A majority of the curves follow the frequently cited equation from Hollands. However, not all curves can be drawn for each plot, as the range of validity is exceeded in some cases. The correlation from Eismann (2015) shows a significant deviation from the others. However, most curves diverge slightly with increasing *Ra*. The differences increase with greater inclination angles.

The CFD model shows a good fit for the correlations from Tab. 2. For higher Rayleigh numbers, the computed Nusselt numbers deviate slightly from the majority of curves and match closer to the equation from Eismann (2015). Overall, the simulated set of parameters is in good agreement to the empirical results collected in the last decades. Given this agreement, it can be concluded that the CFD model is able to describe the physical effects of the heat transfer well. Even for $Ra_{\varphi} > Ra_c = \{1708, 5830\}$ when the flow is characterized by convective rolls (cf. Hart (1971)), the model is capable of computing the heat transfer accurately.



Fig. 2: Validation of the CFD model results (\Box) with Nusselt correlations (–) from literature for five different inclination angles. The plots show a good fit between the numerical and analytical results.

3.3 Parametric Study

For all sets of parameters, the heat flow rates, material properties, and temperatures have been computed to obtain Nusselt and Rayleigh numbers. For each inclination, the results are shown in Fig. 3. The simulation results indicate similar shaped Nusselt curves as given in the literature. To describe the dependence of Nu and Ra the following expression has been used:

Nu = $[(1 + (C Ra^n)^b)]^{1/b}$ (eq. 4) C, n, b: Parameters for non-linear least square regression

This equation was also used by ElSherbiny (1996) to describe the convective heat transfer for cavities which were heated from above. Fig. 3 shows that this approach can likewise be used to describe the heat transfer for cavities heated from below. A non-linear least square fit has been performed to obtain a set of parameters for eq. 4. The data fits hold coefficients of determination and root-mean-square errors as: $R^2 = \{0.992, 0.994, 0.991, 0.985, 0.983, 0.923\}$ and $RMSE = \{0.184, 0.128, 0.135, 0.158, 0.126, 0.079\}$. This confirms the good fit of the equation for the simulation results.

The derived equations were used to compute the heat transfer coefficients for different widths, inclination angles and temperature differences ΔT for an Argon-filled cavity. Fig. 4 shows contour plots of *h* with variable cavity widths and temperature levels for the front $\varphi_f = 40^\circ$ and back $\varphi_b = 140^\circ$. Furthermore, the contours for the equations from Hollands et al. (1976) (for the front) and ElSherbiny (1996) (for the back) have been plotted to compare them with the CFD results. It has to be noted, that the empirical correlations are not valid for all aspect ratios which were used for computation. However, these correlations were used to make a comparison possible and show any deviations. White spaces surround the contours as they are capped to the valid *Ra* and φ ranges of the equations.



Fig. 3: Nusselt vs. Rayleigh number for six inclination angles (φ). The curves (–) have been determined by a non-linear least square fit. Simulation results (\Box) were obtained by a parametric study for a typical operation range of IGFPCs.

As expected, there is a difference between the heat transfer at the front and back side of the collector. Hart (1971) has shown that a cavity which is heated from above has a more stable flow regime as compared to the cavity heated from below. This is resulting for both the empirical calculation and the CFD results. It is $h_b < h_f$ in both cases. Moreover, there is a range of W where h rises significantly. If $W < W^* \approx 12 \text{ mm}$, h increases, whereas for larger widths $\partial h / \partial W < 0$.

A comparison between the empirical and the CFD results at the front cavity shows that for 10 < W < 20 mm the contours are different. Hollands et al. (1976) equation reveals a local minimum of *h* for a given ΔT and variable widths. This is not the case for the CFD model. This effect can be explained by the last addend in the correlation of Hollands et al. (1976) which is creating a buckling to the *Nu-Ra* curve. Hence, the CFD model differs from the empirical solution. The maximum deviation is 25.8 % and the RMS deviation is 0.237 W m⁻²K⁻¹ or 7.3 %. Nevertheless, for both contours, the sensitivity of *h* to *W* decreases with increasing values of *W*. For $\Delta T \approx 35$ K and W > 20 mm *h* becomes nearly independent of *W*.

When comparing the empirical with the CFD results at the back side cavity, a greater amount of similarity is visible. The maximum deviation is 16.9 % and the RMS deviation is 0.181 W m⁻²K⁻¹ or 9.1 %. The correlations derived from the CFD model show a greater $|\partial h/\partial \Delta T|$ for W > 20 mm. Yet, the values of h are in the same order of magnitude for both contours.



Fig. 4: Contour plot of the convective heat transfer coefficient (*h*) with respect to variable cavity widths (*W*) and temperature differences (ΔT). On the left, the Nusselt correlations of Hollands et al. (1976) and ElSherbiny (1996) have been used. On the right, the values were computed using equation 4. The front values (subscript *f*) are shown for an inclination of 40° and the ones on the back side (subscript *b*) for 140°. White spaces surround the plots and represent capped areas in which the used equations exceed validity limits for Rayleigh number (*Ra*) and inclination angle (φ). Argon was considered as the cavity gas.

4. Conclusions

The convective heat transfer inside the enclosed cavity of IGFPCs can partially be computed using Nusselt-Rayleigh number correlations from the literature. An analysis of these equations has shown that their validity range does not cover both high aspect ratios and the entire spectrum of Ra and φ . CFD simulations were used to obtain a new set of correlations which can be used for the entire operating range of IGFPCs. The expression $[(1 + (C Ra^n)^b)]^{1/b}$ was found to be precise for describing the *Nu-Ra* dependence for the following set of inclination angles: $\varphi = \{10,40,70,110,140,170\}$ and this range of Rayleigh numbers: $Ra < 3.2 \times 10^5$. The results confirm that convective losses of IGFPCs occur predominantly at the front side of the collector. For the rear cavity, the flow pattern is subcritical and therefore the losses are smaller for the most parameter sets. On the front side, the heat transfer coefficient h_f is more sensitive to ΔT and W, and thus more sensitive to Ra. This gives substantial evidence, that the absorber position is of significant importance for IGFPCs. Placing it asymmetrically inside the cavity can lead to a performance benefit without having to increase the glass spacing. Consequently, this allows manufacturers to assemble thinner collectors, reduce costs for the edge seal material and thus reduce collector costs.

Overall, the concept of IGFPCs offers potential cost reductions for solar district heating due to its design and production characteristics. The presented study introduced a new set of correlations for describing the convective losses of IGFPCs. Using these equations allows engineers to design IGFPCs with minimized convective losses and to find a balance between material cost (edge seal material) and efficiency (ideal distance between absorber and glass cover). As convective losses represent roughly a third of the overall losses of flat-plate collectors, the influence of design changes on the collector performance can be estimated with the derived equations. However, the equations have not yet been fully validated through comparison with experimental data. Hence, experimental prototype tests are needed in order to confirm the validity of the equations and making them reliable for practical design.

As the aforementioned results focus on the convective heat transfer for the cavity of IGFPCs, there is further research potential on the radiative-convective effects. Another parametric CFD study including radiation allows for findings which demonstrate the share of radiation in the total heat transfer.

5. Acknowledgments

The work presented in this paper was funded by the Federal Ministry of Economic Affairs and Energy of the Federal Republic of Germany within the 7th Energy Research Program under the project "flexLAC" (Project ID 03ETW015-A). The overall aim of "flexLAC" is to design a mass-producible insulated glass flat-plate collector which is able to reduce heat generation costs for solar district heating.

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Property	Symbol	Validation setup	Parametr. study	Unit
Width	W	30	5 - 50	mm
Length	L	1440	2500	mm
Depth	$\frac{D}{2}$	432	750	mm
Cells in <i>x</i>	N_{x}	500	750	-
Cells in y	N_y	150	225	-
Cells in z	N_z	30	15	-
Cell count	Ν	2,250,000	2,531,250	-

Tab. 3: Mesh configurations for validation and parametric study

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Tab. 4: Constants for the numerical and analytical analysis

Name	Symbol	Values	Unit
Indilic	Symbol	values	Unit
Earth's acceleration	g	9.81	m s ⁻²
Roughness glass	κ_{gl}	0.0010	mm
Roughness side walls	κ_w	0.0016	mm
Molar mass Air	M_{Air}	28.959	kg kmol ⁻¹
Characteristic length Air	σ_{Air}	3.711	Å
Energy parameter Air	\mathcal{E}_{Air}	78.600	К
Degree of freedom Air	f _{Air}	5	-
Molar mass Argon	M_{Argon}	39.948	kg kmol⁻¹
Characteristic length Argon	σ_{Argon}	3.542	Å
Energy parameter Argon	\mathcal{E}_{Argon}	93.300	K
Degree of freedom Argon	<i>f</i> _{Argon}	3	-

Performance Analysis of a Solar Assisted Heat Pump System for Inbin Grain Drying

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Abstract

A novel solar assisted heat pump (SAHP) system for in-bin grain drying was proposed to solve the problems of poor uniformity and long drying time of grain in depot with higher initial water content in high grain piles. The effects of different operational parameters on the drying performance were numerically and experimentally investigated. The experimental results indicated that the average water content of 3,760 tons of grain dropped from 12.9% to 12.5% after 42 hours of drying. The specific moisture extraction rate of the proposed system and the exergy efficiency of the grain bin were 1.934 kg/kWh and 40.27%, respectively. The operating cost of SAHP grain drying decreased from 5.57 \$/t to 1.43 \$/t compared with the grain drying machine for the same drying weight. The daily drying capacity increased from 166 t/d to 334 t/d compared with the mechanical ventilation drying for the same water content reduction rate. This investigation provided guidance for expanding future researches on the SAHP system applied for in-bin grain drying.

Keywords: Solar assisted heat pump, In-bin grain drying, Heating capacity, Drying capacity

1. Introduction

China is the largest grain producer in the world, with the national grain production reaching 669.5 billion kilograms in 2020, of which the output of the three main grains, including rice, wheat, and corn, reached 92%, facing the problem of large drying energy consumption (National Bureau of Statistics of China, 2020). Currently, the grain bin mainly uses the grain drying machine and mechanical ventilation drying equipment for grain drying (Hadibi et al., 2021; Migo-Sumagang et al., 2020; Van Hung et al., 2018). Solar thermal integrated with grain drying is applied to mitigate the contradiction between energy consumption and drying time. Moreover, the combination of solar thermal with heat pump for grain drying can contribute to working in a variety of weather conditions (Xu et al., 2021), especially at night and on cloudy days. Therefore, the integration of solar energy with the heat pump is an economical and efficient grain drying method.

However, as shown in the open literature, many researches have carried out on small-scale grain drying (less than 500 tons) based on solar collectors and heat pump. For example, Hasan Ismaeel and Yumrutaş (Hasan Ismaeel and Yumrutaş, 2020) proposed a solar assisted heat pump system for 50 kg/h wheat drying with an underground storage tank to store more solar heat and dry the wheat steadily. The results showed that the COP of the entire system could be up to 4.3. Li et al. (2018) designed a 300 tons of corn drying system combined multistage series heat pump with the heat pipe, reducing the water content of corn from 34% to 14% with an air flow rate of 132,543 m³/h. Experimental results showed that the drying cost per unit corn decreased by 22.4% compared with coal-fired drying. In summary, large-scale in-bin grain drying is becoming one of the leading researches and application fields of solar assisted heat pump technology.

Nevertheless, the increase in drying capacity would result in a decrease in drying uniformity and drying speed. Besides, the high temperature and high water content of grain would lead to the reduction of whiteness, affecting the quality of grain. Many literatures have conducted experimental and simulated researches on improving drying uniformity, reducing drying time, and maintaining grain quality. In this respect, Ziegler et al. (2021) evaluated the effect of moisture content, temperature, and storage time on the corn quality. It can be found out that keeping the water content and temperature at 14% and 25°C and storing the corn for 6 months were the recommended

operating conditions for the bioactive properties of the corn. However, most SAHP systems are not convenient to convert from the heating to the dehumidification scenario, resulting in low working efficiency during rainy days. Moreover, exhaustive researches on evaluating the effectiveness of grain drying are still needed. Therefore, it is necessary to further improve the uniformity in the experiment and discuss the drying effectiveness in the simulation under different weather conditions to expand future researches on in-bin grain drying.

A novel SAHP system applied for in-bin grain drying is proposed to solve the difficulties of poor uniformity and long drying time of grain with higher initial water content in high grain piles. This research aims to evaluate the combined performance of the SAHP system under different working scenarios and analyze the effect of operation parameters on grain drying.

2. Description of the SAHP drying system

The SAHP drying system is divided into three subsystems in Fig. 1: (a) the solar collector subsystem uses solar energy to heat the ambient air, (b) the heat pump subsystem consisting of condenser, expansion valve, evaporator, compressor, and blower, and (c) the grain bin subsystem including air supply pipes, air return pipes, and grain stirrer. As shown in Fig. 2, the SAHP system needs some switches with different drying scenarios according to weather conditions during the grain drying period. he SAHP system has four operating scenarios, which are (a) the solar collector working alone at the time of strong solar radiation, (b) the heat pump working alone at night, (c) the solar collector and the heat pump working together at the time of poor solar radiation, and (d) the heat pump dehumidifying on overcast and rainy days, respectively.



Fig. 1: Schematic diagram of the SAHP system applied for in-bin grain drying



Fig. 2: Four operation scenarios of the entire system under different weather conditions

3. Mathematical model

3.1. Solar collector

The energy equation of the solar collector is (Hawlader and Jahangeer, 2006):

$$M_{a}c_{p,a}\frac{dT_{a}}{dt} = A_{c}\eta_{c}I_{T} + m_{a}c_{p,a}\left(T_{a,out} - T_{a,in}\right)$$
(eq. 1)

where M_a is the weight of air in the collector, kg; $c_{p,a}$ is the specific heat capacity of air, J/(kg·°C); T_a is the air temperature, °C; A_c is the collector area, m²; η_c is the thermal efficiency, %; I_T is the solar radiation intensity, W/m²; m_a is the mass flow, kg/s; $T_{a,in}$ and $T_{a,out}$ are the temperature of the air at the inlet and outlet respectively, °C.

The thermal efficiency of the solar collector is calculated by Eq. (2) (Duffie et al., 2020):

$$\eta_c = \frac{\int_{t_1}^{t_2} Q_c dt}{A_c \int_{t_1}^{t_2} I_T dt}$$
(eq. 2)

where Q_c is the effective heat collection of the solar collector, kW.

3.2. Heat pump

The heat transfer of condenser between refrigerant and air is calculated (Iu, 2007):

$$Q_{con} = \varepsilon \left(mc \right)_{\min} \left(T_{ht,in} - T_{lt,in} \right)$$
 (eq. 3)

where Q_{con} is the heat transfer rate of the condenser, kW; $T_{ht,in}$ and $T_{lt,in}$ are the inlet temperature of high temperature side and low temperature side, °C.

The input power of the compressor can be calculated as follow (Kong et al., 2017):

$$W_{com,in} = \frac{W_{com}}{\eta_{mo} \times (\lambda_T + 0.0025 \times (T_{eva} - 273.15))} + \frac{W_m}{\eta_{mo}}$$
(eq. 4)

where η_{mo} is the motor efficiency, %; λ_T is the temperature coefficient; T_{eva} is the evaporation temperature, K; W_m is the friction power, kW.

3.3. In-bin grain drying model

To further describe the variation of grain water content, the modified thin-layer drying model is adopted for this research. The in-bin grain drying model consisted of the following three control equations.

(1) Humidity control equation (Hossain et al., 2003):

$$\Delta H = -\left(\frac{\rho_g}{G_a}\right) \left(\frac{\Delta W C_g}{\Delta t}\right) \Delta z \qquad (eq. 5)$$

where ΔH is the specific humidity different, kg/kg; ρ_g is the density of grain, kg/m³; ΔWC_g is the water content different of grain, %; Δt is the time different, s; and Δz is the height different of grain in grain bin, m.

(2) Temperature control equation (Hossain et al., 2003):

$$\Delta T = \frac{\left(\left(c_{p,v} - c_{p,w}\right)T + r_{vap}\right) \times \Delta W C_g}{c_{p,g} + c_{p,w}M_g + \left(c_{p,w} - c_{p,v}\right) \times \Delta W C_g + \frac{G_a}{\rho_g} \times \left(c_{p,a} + c_{p,v}H\right) \times \frac{\Delta t}{\Delta z}}$$
(eq. 6)

where ΔT is temperature different, °C; r_{vap} is latent heat of vaporization, kJ/kg; $c_{p,a}$, $c_{p,g}$, $c_{p,v}$ and $c_{p,w}$ are specific heat of air, grain, vapor and water, kJ/(kg·K).

(3) Water content control equation (Dai et al., 2008):

$$\frac{WC_g - WC_e}{WC_0 - WC_e} = \exp\left(-kt^{0.64}\right)$$
(eq. 7)

where WC_0 and WC_e are initial and equilibrium water content of grain, %.

3.4. Exergy and economic analysis

The exergy flow of air and refrigerant is shown in Eq. (8) and Eq. (9), respectively (Singh et al., 2020a).

$$Ex_{a} = m_{a}c_{p,a}((T_{a} - T_{o}) - T_{o}\ln(\frac{T_{a}}{T_{o}}))$$
(eq. 8)
$$Ex_{ref} = m_{ref}((h_{ref} - h_{o}) - T_{o}(s_{ref} - s_{o}))$$
(eq. 9)

The payback period of the SAHP system is calculated by Eq. (10):

$$P_{p} = \frac{C_{ii}}{T_{s} - C_{ii} - C_{oc}}$$
(eq. 10)

where C_{ii} and C_{oc} are the initial investments and operating costs of SAHP system, respectively; T_s is the total sales of grain, \$.

3.5. Performance evaluation

The specific energy consumption (*SEC*), specific thermal energy consumption (*STEC*), and specific moisture extraction rate (*SMER*) are calculated to evaluate the energy consumption in the drying process (Singh et al., 2020b).

$$SEC = \frac{\int_{t_1}^{t_2} (W_{in,com} + W_{in,bl} + W_{in,gs} + I_T + Q_{con})dt}{M_w}$$
(eq. 11)

$$STEC = \frac{\int_{t_1}^{t_2} (I_T + Q_{con}) dt}{M_w}$$
(eq. 12)

$$SMER = \frac{M_{w}}{\int_{t_{1}}^{t_{2}} (W_{in,com} + W_{in,bl} + W_{in,gs} + I_{T} + Q_{con})dt}$$
(eq. 13)

where M_w is the weight of water removed from grain, kg.

4. Results and discussion

4.1. Performance of SAHP system

As shown in Fig. 3, the combined operation performance of solar collectors and heat pump on a typical sunny day in Kunming was described. The solar radiation was similar to sinusoidal variation, rising from 253 W/m² to 1,165 W/m² and then dropping to 135 W/m². The temperature gradually rose from 7.8°C to the highest temperature of 16.5°C, then slowly dropped to 15.4°C. The heating capacity of solar collectors was greatly affected by solar radiation, which was also similar to sinusoidal variation, rising from 9.2 kW to 83.5 kW and then dropping to 10.7 kW. The heat produced by the heat pump was less affected by the ambient temperature and the solar radiation, gradually rising from 58.23 kW to the maximum heat produced by 67.39 kW and then slowly falling back to 65.88 kW. Between 11:00 and 16:00, the fraction of solar energy was greater than 0.4, in which it was recommended to turn on the solar collector to obtain better economic performance.



Fig. 3: Simulation of combined operation performance of SAHP system in a typical sunny day

4.2. Simulation of in-bin grain drying

The width, depth, and height of the grain pile model are set to 1 m, 1 m, and 2 m, respectively, and the initial water content of the grain is assumed to be 20%. Fig. 4(a)-(c) show the influence of temperature and relative humidity of inlet air on the grain drying. Take the inlet air temperature at 20°C and relative humidity at 60% as an example. The initial and final drying stagnation times are 4 h and 8 h, respectively, indicating that the effectual drying time is 12 h, and the water content of grain after drying is 17.56%. Based on the analysis of the inlet air with relative humidity of 60%, when the temperature of the inlet air rises from 20°C to $30/40^{\circ}$ C, the effectual drying time increases from 12 h to 16/18 h, and the water content of grain after drying decreases from 17.56% to 15.76/14.33%. In addition, with the decrease of the relative humidity of the inlet air, the drying effect gets better. For the inlet air with a relative humidity of 30%, the final drying stagnation time decreases to 0 when the temperature rises to 35° C. The inlet air with the relative humidity of 20% has no initial drying stagnation time and final drying stagnation time, indicating that the grain can still be dried by continuing to ventilate.

Fig. 4(d) shows the influence of the wind speed of the inlet air on the drying effect of corn. As the wind speed increases from 0.1 m/s to 0.2/0.3/0.4/0.5 m/s, the drying time decreases from 62 h to 35/26/23/21 h. Fig. 4(e)-(f) describe the effect of wind speed and drying time on the grain drying zone. When the drying time is 10/20/30/40/50 h, the height of the corresponding drying zone is 0.1-0.9 m, 0.3-1.3 m, 0.6-1.6 m, 0.9-2 m, and 1.2-2 m, respectively. For the inlet air with a velocity of 0.5 m/s in Fig. 4(f), it is analyzed that the height of the drying zone corresponding to the drying time of 4/8/12/16 h is 0-2 m, 0.6-2m, 0.98-2 m, and 1.5-2 m respectively.



Fig. 4: Simulation results of in-bin grain drying

4.3. Drying experiment of SAHP drying system

As shown in Fig. 5, the influence of air parameters at the inlet of the grain bin on grain water content under different weather conditions in summer was tested. The ventilation time on April 30 was from 11:00 to 15:00, during which the solar radiation was relatively good; therefore, ambient air was heated by solar collectors separately. The relative humidity of the air at the inlet of the grain bin varied from 20.8% to 19.4%. The temperature varied from 29.2°C to 36.1°C, which was ranged 4.2-7.5°C higher than the ambient temperature.

On May 1, the solar radiation was relatively good from 9:30 to 14:00, so the ambient air was heated only by solar collectors. The solar radiation was reduced from 14:30 to 16:30. Both solar collectors and heat pump were turned on to prevent the inlet temperature from being too low. The relative humidity of the inlet air varied from 16.9%

to 34.5%, and the temperature varied from 25.2°C to 38.5°C, which was 3.1-11.85°C higher than the ambient temperature.

The solar radiation is unstable on May 3. Both solar collectors and heat pump were turned on to heat the ambient air during the day. While the solar radiation intensity was approximately zero after 16:00, the air temperature rose gradually tended to be stable when the system only had the heat pump for heating. The variation of inlet air temperature was from 22.4°C to 34.7°C, relative to the ambient temperature rise was 7.4-13.8°C, the average temperature rise was 9.3°C, and the relative humidity varied from 14.8% to 32.2%.

For May 4, the ambient air was heated by the combination of solar collectors and heat pump as the solar radiation was poor and unstable between 9:00 to 17:00. Since then, the heat pump was switched to the dehumidification mode for the relatively high humidity of the ambient air, and the temperature rise of the inlet air tended to be stable. The inlet air temperature varied from 22.4°C to 34.7°C, which is 7.9-14.2°C higher than the ambient temperature, the average temperature increase was 9.4°C, and the relative humidity variation range was 20.7-37.7%.

The heat pump and solar collectors were turned on May 5 because of the unstable weather. The variation range of air temperature in the grain bin was 26.4-41.8°C, the inlet air temperature rose by 8.5-14.7°C compared with the ambient temperature, and the relative humidity of inlet air varied in the range of 13.6-36.0%.

The initial value of the average water content of grain was 12.94%, and the average water content of grain after ventilation and drying on April 30, May 1, May 3, May 4, and May 5 was 12.9/12.75/12.61/12.57/12.5%, respectively. Fig. 6 showed the changes in temperature and water content of grain in each layer. The temperature and water content measurement points were located directly above the branch air pipe, in which the first layer was 50 cm away from the branch air pipe, and the spacing of each layer was 100 cm. The temperature of the first layer was 23.7/24.7/26.3/27.1°C after ventilation for 0/2/4/6 h, respectively, while the temperature of grain in the area 2 m above the bottom of the grain pile was stable at 20.8°C. The initial values of the average water content of the grain in layers 1-5 were 12.7/12.8/12.7/13.1/13.4%, respectively, the average water content after drying was 12.4/12.7/12.4/12.6/12.7%, respectively, and the water content reduction rate varied from 0.36% to 4.97%.



Fig. 5: Experimental results of supply air temperature and relative humidity with different weather conditions in summer



Fig. 6: Experimental results of temperature and average water content changes of grain in different layers

4.4. Energy consumption and exergy evaluation

Fig. 7 depicted the calculation results of *SEC*, *STEC*, and *SMER* under four scenarios. The maximum and minimum values of *SEC/STEC* were 3.16/2.7 MJ/kg in scenario one and 1.863/1.48 MJ/kg in scenario three, respectively. The reason was that 11,530 m³/h and 34,800 m³/h of ambient air was heated by solar collectors in scenario one and SAHP system in scenario three, respectively, resulting in more water content removed from grain in scenario three than in scenario one. The calculated results of *SEC/STEC* in scenario two (2.31/1.78 MJ/kg) are lower than that in scenario four (2.75/2.04 MJ/kg). The reason was that the inlet air flow rate of scenario two (34,800 m³/h) was larger than that of scenario four (23,270 m³/h), and RH of inlet air in scenario two (21.6%) was less than that in scenario four (23.1%), resulting in the removal of water content in scenario two was larger than that of scenario four (23.1%), resulting in the removal of *SMER* were 1.934 kg/kWh in scenario three and 1.138 kg/kWh in scenario one, respectively.



Fig. 7: Calculation results of SEC STEC and SMER under four scenarios

The exergy flow of inlet and outlet air and exergy destruction of each component of the SAHP grain drying system were described in Fig. 8. The maximum and minimum exergy flow of heated air at the inlet of the grain bin were 14.5 kW in scenario three and 10.84 kW in scenario four, respectively, which was due to the additional air heated by solar collectors in scenario three compared with scenario four. Since the temperature and pressure of the inlet air decreased in the process of grain drying, the exergy destruction and exergy efficiency of the grain bin under four scenarios were 7.9/8.09/8.96/7.31 kW and 39.32%/39.08%/40.27%/35.54%, respectively.

The exergy destruction and exergy efficiency of solar collectors in scenario one and in scenario three were

62.4/46.16 kW and 6.67%/5.26%, respectively. The reason that exergy efficiency of solar collectors was lower than thermal efficiency was that the outlet air temperature was lower than the apparent solar temperature. The exergy destruction and exergy efficiency of the condenser in scenario two, scenario three, and scenario four were 5.1/5.36/4.9 kW and 45.51%/44.16%/46.79%, which was due to higher outlet air temperature in scenario four than that in scenario two and scenario three.



Fig. 8: Exergy analysis of the SAHP grain drying system under four scenarios

4.5. Economic evaluation

Fig. 9 and Table 1 take the mechanical ventilation drying and the grain drying machine as a reference to compare and analyze the economics of the SAHP grain drying. The mechanical ventilation drying generally uses the air supply system to directly send ambient air into the grain bin for drying, whose advantages are the lowest operating cost, initial investment, and payback period, which are 1.06 \$/t, 22,930 \$, and 0.14 years, respectively. Although up to 5,000 tons of grain can be dried, the air supply temperature of mechanical ventilation is the same as the ambient temperature, resulting in longer drying time, poor drying uniformity, and being affected by ambient air.

The ambient air can be heated to 50° C by the grain drying machine, which has the advantages of better drying uniformity and flexible operation modes. However, the drawback of the grain drying machine is the highest operating cost, initial investment, and payback period, which are 5.3 times, 2.4 times, and 3.57 times that of mechanical ventilation drying, respectively. The reason for the high operating cost is that the proportion of fuel cost is 65.6%; in addition, the daily drying capacity of the grain drying machine is relatively small.

The average air supply temperature of the SAHP system for in-bin drying is 40°C. The daily drying capacity of grain is 334 tons/d, which is 2 times and 4.3 times of mechanical ventilation drying and grain drying machine. The operating cost, initial investment, and payback period of SAHP grain drying are respectively 1.485 \$/t, 45,850 \$, and 0.33 years, which are higher than mechanical ventilation drying due to the high maintenance cost of machinery. The SAHP grain drying has the advantages of larger daily drying capacity, better drying uniformity, and higher air supply temperature compared with the mechanical ventilation drying. Moreover, the SAHP grain drying solves the shortcomings of the grain drying machine due to lower operating costs and initial investment, more weight of dryable grain, and larger water content reduction. In summary, the SAHP grain drying is an economical and efficient method to gradually replace mechanical ventilation drying and grain drying machine.



Fig. 9: Economic comparison of three drying technologies

Parameters	Mechanical ventilation drying	Grain drying machine	SAHP drying
Maintenance cost (\$/t)	0.56	1.53	1.12
Labor cost (\$/t)	0.15	0.38	0.08
Electricity cost (\$/t)	0.29	0.14	0.23
Fuel cost (\$/t)	0	3.52	0
Operating costs (\$/t)	1	5.57	1.43

Table 1. Operating costs comparison of three grain drying technologies

6. Conclusion

For the purpose of evaluating the comprehensive performance of solar collectors and heat pump on grain drying, the experimental and numerical investigations were performed. The main conclusions are summarized as follows:

(1) The SEC, STEC, and SMER of the SAHP grain drying system in scenario three are 1.863 MJ/kg, 1.48 MJ/kg, and 1.934 kg/kWh, respectively.

(2) The exergy destruction and exergy efficiency of solar collectors, condenser, and grain bin in scenario three are 46.14/5.36/8.96 kW and 5.26%/44.16%/40.27%, respectively.

(3) The initial investment of SAHP grain drying is 16.7% lower than that of the grain drying machine for the same drying weight, and the operating cost decreased from 5.64 \$/t to 1.485 \$/t for the same drying weight. The daily drying capacity increased from 166 t/d to 334 t/d compared with the mechanical ventilation drying for the same water content reduction rate.

(4) The proposed system solves the shortcomings of conventional drying methods due to quickly and uniformly drying the large-scale grain at a lower operating cost.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (No. 51961165110).

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H-02. Thermal Energy Storage

Experimental characterization of a latent heat storage unit with lithium nitrate inside finned cylinders for assisting solar air heating

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Abstract

Thermal energy storage technologies offer a promising solution for reducing the mismatch between heat demand and solar heat supply. Heat storage has huge potential for application in solar facilities for process heat at medium temperatures, nowadays not much explored. In this study, a small-scale latent heat storage unit is implemented and experimentally investigated. Lithium nitrate salt is selected as the storage material for its excellent properties. It is encapsulated inside vertical externally finned cylinders. Air is the heat transfer fluid. The thermal storage unit is integrated into an existing innovative prototype for direct solar heating of air which can provide hot air up to 300 - 400 °C using a 79.2 m² linear Fresnel collector field. TES charge and discharge tests are performed, and they are critically analyised. Results allow the thermal characterization of the storage unit and underpin critical aspects for scaling up. The experimental data obtained are relevant information for the numerical models tuning and validation.

Latent heat storage; solar heat for industrial processes; Linear Fresnel collector; Lithium nitrate; phase change material.

1. Introduction

Solar thermal technologies are a suitable solution for industrial heat demand in the low and medium temperature range, (Sharma *et al.*, 2017). Solar intermittency and variability can preclude matching the solar heat supply with industrial demand, representing an important obstacle to the implementation of solar thermal system at a large scale.

Thermal Energy Storage TES represents a key technology for mitigating this drawback and increasing the dependability of solar thermal systems. Extensive research has been carried out during the last decades on TES applications for low-temperature domestic heating systems as well as for large-scale and high-temperature concentrated solar power CSP. Medium temperature TES, especially suitable for solar heat for industrial process SHIP applications, has received limited attention, despite its high potential. (Crespo *et al.*, 2018) offers an extensive review on TES systems, analyzing the state of the art of technology and materials. The authors highlight the potential of latent heat storage for industrial applications in the range of temperature 150 - 400 °C.

The use of air as heat transfer fluid is widespread in the industry. Many processes use hot air for drying, curing, finishing a large variety of products, materials, or residues. Process air heating is currently achieved by consuming fossil fuels or electricity, although solar thermal technologies are rising as an interesting alternative.

(Famiglietti *et al.*, 2020) proposes direct air heating inside linear concentrating collectors in order to provide process air at 300 - 400°C, with no need for a primary heat transfer fluid HTF (oil, pressurized water) neither HTF/air heat exchanger. Either linear Fresnel Collectors LFCs or Parabolic Trough Collectors PTCs are suitable for the purpose. In the original layout studied, an automotive turbocharger is coupled with the solar field allowing to minimize or avoid the pumping power required, as numerically demonstrated in a further study, (Famiglietti *et al.*, 2021). A first-generation prototype of the Turbo-assisted Solar Air Heater T-SAH is currently installed at Carlos III University Campus of Madrid, Fig.1 offers a scheme.

In this study, an experimental medium-temperature latent heat storage unit, integrated into the existing T-SAH prototype, has been designed, built, and tested. The Lithium Nitrate salt LiNO₃ has been selected as storage

material due to its suitable melting temperature of 254 °C and its high specific latent heat of 360 kJ/kg, about three times higher than other alternatives.

2. Experimental setup

The heat storage unit is installed on a building rooftop of the Carlos III University of Madrid. It is integrated into the existing experimental prototype devised for solar air heating T-SAH, Fig.1. The innovative T-SAH uses three first generation commercial linear Fresnel collectors (Solatom^{TM)} in series, reaching 79.2 m² of capturing area. Two parallel electrical blowers *ac* (Elektor SD22 FU 80/1,1) fed by a frequency converter are connected to the inlet of the turbo-compressor *c*. A small-size automotive turbocharger is used for increasing air density inside the solar field, this way reducing pressure drops, and recovering compressing power through the attached turbine *e*. The air circuit is instrumented with class A thermocouples type K, and pressure sensors, having respectively estimated total uncertainty of ± 2.0 °C and ± 25 mbar, while an airflow sensor with a total uncertainty of $\pm 3\%$ (Schmidt 30.015 MPM) is installed at the atmospheric inlet. Piping is thermally insulated using mineral wool and glass fiber. The T-SAH prototype has been analysed in details in (Famiglietti and Lecuona, 2021a) and (Famiglietti and Lecuona, 2021b).

The TES unit is mounted downstream of the turbine, Fig.1. A manual switching valve connects the TES directly to the solar air heater, as required during the charging test, which can be bypassed if required.



Fig. 1. Experimental setup scheme, Linear Fresnel Collector LFC, auxiliary compressor ac, turbo-compressor c, turbine e, thermal storage unit TES.

A "shell and tube" design is chosen for the TES heat exchanger configuration, in a single row layout. There, the air flows inside a straight channel across four vertical tubes filled with the phase change material (LiNO₃). Commercial tubes with round transversal fins appeared as the best solution for improving the heat transfer rate in the airflow side, keeping a low-cost and easy manufacturing. For the air channel, some air conditioning ducts are considered due to the low cost and their widespread availability on the market as they are used for air conditioning in buildings.

Fig. 2 (a) reports a 3D drawing of the TES core. An air channel with a square cross-section of 600 mm and a length of 500 mm is chosen. The lithium nitrate salt is filled inside four externally finned cylinders made of stainless steel, having an internal diameter of 76.1 mm, 2.9 mm wall thickness, an overall height of 570 mm, and a finned height of 490 mm. The cylinders are externally finned with welded helicoidal corrugated fins of carbon steel, with a height of 35 mm and thickness of 0.7 mm. The distance between fins is 6 mm. The upper and lower no-fins apertures are closed with removable flanges. The cylinders are placed vertically and adjacent one to another, in parallel to the perpendicular airflow, Fig. 2(a).

One of the inner four cylinders is instrumented with type K thermocouples, Fig. 2(b). They are placed in the

central vertical axis, at the upper as well as at the lower part and in the middle. Additional thermocouples were placed on the horizontal plane at the medium height cross-section to detect temperature gradients in the horizontal radial direction, Fig. 2 (b). To correctly position the thermocouples inside the tube a thin structure is needed as shown in Fig. 3(b). They are fixed on the upper flange and positioned with the aid of three separators made of stainless steel and 1 mm thickness, then aligned using two vertical threaded rods, Fig. 3(b). Two thermocouples measure air temperature at the inlet and outlet of the TES channel.



Fig. 2. TES layout and finned cylinder. (a) Finned cylinders inside insulated the air channel. (b) Finned cylinder instrumented.

Fig. 3(a) depicts the whole air channel. A 100 mm diameter round duct connects the TES core with the T-SAH outlet (turbine exit).



Fig. 3. TES air channel. (a) 3D view. (b) Thermocouples inside the instrumented tube, with separators plates.

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The TES unit is assembled and is integrated downstream the T-SAH turbine. The finned cylinders are filled with $LiNO_3$ in a fine granular state. A second filling operation was devised after the first melt. Fig. 4 (a) shows a single finned cylinder partially filled with $LiNO_3$. The thermocouples assembly is prepared as in Fig. 4(b), to be inserted into the instrumented cylinder before filling it with salt.



(a)



(b)

Fig. 4. TES preparation. (a) Finned cylinder; (b) Thermocouples and supporting structure.

Then the four cylinders sealed with their flanges are assembled inside the square duct as in Fig. 5(a). Once the TES core was assembled, it has been covered with a mineral wool insulation of 150 mm thickness and covered with aluminum foil, Fig. 5(b). The connection duct with the turbine exit is installed and insulated.





(b)

Fig. 5. TES components. (a) Cylinders and inside the square duct, (b) insulated TES box, air duct before insulation.

Each of the four cylinders is initially filled with 2.6 kg of commercial LiNO₃ in a granular state, occupying 100% of the internal volume of 2.18 L, thus with an average density of 1,190 kg/m³. The weight of an empty finned cylinder is 8.9 kg. The density of solid salt at room temperature is higher, although in the literature the exact value diverges from one source to another, between 1,780 kg/m³ (Tamme, R. et al. 2008) to 2,380 kg/m³ (^{Chemicalbook)}. For that reason, a first melting and solidifying cycle has been carried out, before inspecting inside the cylinders, as reported in Fig. 6. It shows as the solidified salt fills around 60% of cylinder volume, having a density of 1,990 kg/m³ at room temperature.



Fig. 6. Finned cylinder inspection after first melting/solidifying cycle. (a) Partially filled volume, (b) empty height.

An additional amount of salt of 0.770 kg is filled in each cylinder, reaching a total amount of 3.37 kg of salt per cylinder and 13.48 kg for the whole TES. A melting and solidifying cycle has been repeated before checking again the status of the salt, reported in Fig. 7.

The filled volume with solid salt is now 77% of the total height. The air gap in the upper part of the cylinder allows the volume to increase from a solid to a liquid state. Considering a liquid density at 300 °C of $1,753 \text{ kg/m}^3$, the salt volume at the liquid state is expected to reach 90% of the internal cylinder volume, avoiding the risk of leakage from the upper flange or its rupture. In Fig. 7(a) it can be noticed that during the solidification process, the contracting salt can originate an empty region in the center of the material block similar to a hole. This is caused by the progression towards the axis of the solidification front and the fall of the inner liquid fraction.



Fig. 7. Finned cylinder inspection after the second melting/solidifying cycle with increased salt content. (a) Non-uniform salt block, (b) Empty height showing the thermocouple brackets.

3. Results

Two representative tests were devised for qualitative characterization of the TES unit. The first one allows to obtain the charging and discharging curves and features. The second test reveals the effect of the TES unit on the delivery air temperature of the combined T-SAH and TES prototypes.

Fig. 8 shows the charging and discharging test results. The TES is initially disconnected from the T-SAH. During more than one hour the T-SAH is run alone, with the solar field in tracking mode. When the exit turbine temperature T_4 , higher than 300 °C, is reached, then the TES unit is connected, and the hot airflow starts to heat the finned cylinders. Fig.8 reports the air temperature at the TES inlet T_5 is (a). Due to T-SAH features and sun availability, T_5 is not constant during the charging period, but varies between 300 °C and 350 °C. The temperature of the salt T_s measured at three points of the medium-height transversal cross-section according to Fig. 9(b) is reported in Fig. 8(a). A sensible solid heating period of 65 - 70 min with a rapid temperature rise proceeds the melting process, which lasts approximatively 70 min. Once the salt is completely molten, the temperature starts to rise again during a liquid sensible heating, going up to 280 °C. Air at the TES outlet holds the temperature T_6 , also reported in Fig.8 (a), which shows a smoother time profile than the salt temperature T_s .

Before running the discharging test, the solar field is defocused, and the TES is disconnected from T-SAH for a short time. Meanwhile, the air flowing into the T-SAH cools progressively the components of the air circuit (pipes, receiver, turbocharger). When the air temperature at the turbine outlet T_4 drops below the salt temperature (~ 200 °C) the TES is connected again to the T-SAH, and the airflow starts to cool the cylinders. The solidification process lasts around 75 min, with inlet air temperature T_5 dropping from ~200 °C to ~80 °C. A sensible solid cooling time interval follows. As a consequence of the TES discharge, the outlet temperature T_6 has a slower drop with respect to T_5 .

Fig. 8(b) shows the air mass flow rate through the TES \dot{m}_{TES} , together with the thermal powers \dot{Q}_{a5} , \dot{Q}_{a6} , \dot{Q}_{TES} , Eqs. (1) to (3).

$$\dot{Q}_{a5} = (T_5 c_{p5} - T_{amb} c_{p,amb}) \dot{m}_{TES}$$
 (eq. 1)

$$\dot{Q}_{a6} = (T_6 c_{p6} - T_{amb} c_{p,amb}) \dot{m}_{TES}$$
 (eq. 2)

$$\dot{Q}_{TES} = \dot{Q}_{a6} - \dot{Q}_{a5}$$
 (eq. 3)

The power exchanged between the airflow and the TES shows a peak of 6 kW and ranges between 2 kW and 4 kW during latent heating and cooling, depending on the operating conditions.



(a) (b) Fig. 8. Charging and discharging test. (a) Main temperatures and melting temperature, (b) Thermal power and mass flow rate vs. Local Time LT.

Sensible and latent heat stored during the charging process can be estimated from thermophysical properties of the salt and its container. During sensible heating when at solid-state from ambient temperature (30 °C) to salt melting temperature (254 °C), the overall amount of salt can store $Q_{salt}^{sol} = 1.25$ kWh of heat, considering an average specific heat capacity of 0.414 Wh/kg K, (1.49 kJ/kg K). Considering the specific latent heat of 0.1 kWh/kg (360 kJ/kg), the latent heat stored during complete melting results $Q_{salt}^{salt} = 1.348$ kWh.

The amount of heat stored in the salt during charging, up to complete melting is $Q_{salt} = Q_{salt}^{sol} + Q_{salt}^{melt} = 2.6$ kWh.

The sensible heating of the finned tubes containing the salts is not negligible. The mass of the stainless-steel tube is 3.37 kg, in addition to the 5.7 kg of carbon steel fins. Considering an average specific heat of 0.5 kJ/kg K, the four finned tubes stores $Q_{cyl} = 1.108$ kWh of heat when heated from ambient to salt melting temperature, corresponding to 30% of the amount of heat stored in the salt and finned tube container $Q_{TES,ch}^{cal} = Q_{salt} + Q_{cyl} = 3.7$ kWh.

An experimental estimation of $Q_{TES,ch}^{exp}$ can be obtained by integrating over the charging time τ (excluding liquid heating) the \dot{Q}_{TES} of Eq.3, reported in Fig.8(b).

$$Q_{TES,ch}^{exp} = \int_{\tau_0}^{\tau_m} \dot{Q}_{TES} \langle \tau \rangle \, d\tau \tag{eq. 4}$$

A value of $Q_{TES,ch}^{exp} = 9.14$ kWh is found between the time of charging start τ_0 and the time of complete salt melting τ_m . The much higher value of $Q_{TES,ch}^{exp}$ than $Q_{TES,ch}^{cal}$ is due to heat exchange between airflow and the TES external case. Although the losses to ambient are minimized by the mineral wool thermal insulation, both the square air channel walls and the insulation itself increase their temperature during the charging period, storing a non-negligible amount of heat.

Additional features of melting and solidifying processes can be observed in Fig. 9 (a). It reports, besides three internal salt temperatures $T_{s,up}$, $T_{s,c}$, $T_{s,do}$, the temperature of the salt layer adjacent to the wall $T_{w,up}$, $T_{w,do}$ as in Fig. 9(b).



Fig. 9. The salt temperature during melting and solidification. (a) Temperatures vs Local Time LT, (b) sensors position.

As expected, the salt temperature adjacent to the upstream wall $T_{w,up}$ reaches the melting point at first, followed by the salt temperature at the opposite site $T_{w,do}$. The salt starts to melt from the external layer adjacent to the hot wall of the cylinder, while the core of the salt block is still a few degrees below the melting point. The limited thermal conductivity of the solid salt $k_{salt}^{sol} = 1.348$ W/K m controls the heat transfer to the salt core and the melting front speed from the outer surface to the inner core.

The core temperatures $T_{s,up}$, $T_{s,c}$, $T_{s,do}$ grow smoothly during the melting process, below the theoretical melting temperature $T_{pc} = 254$ °C. The center temperature $T_{s,c}$ is the lowest and the last, which start to raise again for liquid sensible heating. A similar trend is observed during the solidifying process. The wall temperatures $T_{w,up}$ and $T_{w,do}$ drops as first. Then, internal temperatures keep steady around 252 - 253 °C. They are much closer between them than in the melting case, depicting a more homogeneous process. This can be an effect of the higher liquid salt thermal conductivity with respect to solid, $k_{salt}^{liq} = 2.96$ W/K m. Moreover, solidification progresses from the outer surface to the inner core.

The subcooling phenomenon, a typical effect that delays the solidification of some phase change materials, is not observed in our case.

The second test performed considers the joint behavior of T-SAH and the TES. The TES is connected permanently in series with the T-SAH as in Fig.1. From the time when the solar field begins to track the sun, either the T-SAH and the TES undergo a heating transient, which brings up the air temperature at the TES inlet (turbine outlet) T_5 as in Fig. 10(a). The outlet TES temperature T_6 grows slower and below T_5 . After sensible heating of about 2 h, the salt starts melting. Liquid sensible heating takes place as the final step of the charging process, up to 290 °C of salt temperature. Then, the solar field is defocused to simulate a short sun power interruption, as during the appearance of clouds.

Due to the thermal inertia of T-SAH components (pipes, receiver tubes, turbocharger) the temperature drops at the TES inlet T_5 is not instantaneous and the airflow keeps heating the TES for a few minutes. Then it starts to discharge the TES, which begins to solidify. Its effect on the outlet temperature T_6 can be noticed, which remain above 180 °C during a sun power shortage of 45 min, while T_5 drops down to 120 °C.

Subsequently, the sun tracking is restored. The salt keeps solidifying for a few minutes before it starts to melt again, afterwards heated as a liquid. The last part of the experiment is again a full TES discharge. Globally,

the effect of the TES charging and discharging thermal capacity is smoothing the variation of outlet air temperature T_6 with respect to T_5 , which would be the delivery in the absence of TES. Fig.10 (b) reports the exchanged power \dot{Q}_{TES} as well as the solar power gain across the solar field \dot{Q}_u and the power \dot{Q}_{a5} and \dot{Q}_{a6} .



(a) (b) Fig. 10. Effect of TES on delivery hot airflow. (a) Temperature. (b) Thermal power vs Local Time LT.

4. Conclusions

The results obtained during the first experimental tests carried out on the TES unit indicate the viability Lithium Nitrate as phase change material for the range of temperatures typical of the new turbo-assisted solar air heater T-SAH experimented. The shell-and-tube configuration selected for the heat exchanger design, seems a suitable solution, aiming at compactness, simplicity and low-cost, by using commercial finned tubes and air conduits.

The experiments indicate that more than one row of vertical tubes would be needed for increasing the storage capacity and the beneficial effect of TES on T-SAH outputs.

An extensive thermal analysis would be convenient for characterizing the heat transfer phenomena taking place, through the development of a comprehensive numerical model. The experimental data provided would represent a useful information for the numerical model tuning and validation.

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Natural convection heat transfer inside vertical cylindrical solar storage tanks

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Abstract

Natural convection inside a stratified solar storage tank significantly contributes to the rate of heat loss from the tank. However, only a limited number of studies in the literature have investigated the means to predict convection heat transfer coefficient inside the tank. This study presents a numerical investigation of natural convection heat transfer inside a vertical cylindrical storage tank. The simulated results were then used as a benchmark to assess the suitability of existing flat plate correlations to predict the rate of heat loss from such tanks. The results showed that using flat plate correlations lead to deviations in rate of heat loss with up to 23% compared to the numerical results. These findings demonstrate that there is still a need to develop a correlation that can accurately predict convective heat transfer coefficient inside cylindrical storage tanks.

Keywords: Internal natural convection; Internal heat generation; Solar storage tanks; Heat loss; Heat transfer coefficient; Flat plate correlations

1. Introduction

One of the main factors that reduces the thermal performance of a solar water heating system is the heat loss from solar water storage tanks. This is particularly the case when the tank is in standby mode at night, due to lower ambient temperatures compared to the day (Yang et al., 2019). Therefore, the ability to predict the rate of heat loss is vital to effectively optimise the performance of such systems.

Static heat loss to the ambient takes place through a series of heat transfer modes, as shown in Figure 1. The first resistance represents the natural convection heat transfer inside the tank due to temperature gradient between the water and the wall. Heat received from the water is then conducted through the tank wall and insulation before it is lost to the ambient. Although the thermal resistance to conduction through the tank wall and insulation can be easily estimated using Fourier's law (Cengel, 2007), the natural convection heat transfer resistance between the water and the wall is difficult to predict since there are only a limited number of studies that exist on understanding its relation to the rate of heat loss.



Fig. 1: Thermal resistance network for static heat loss to the ambient

The contribution of natural convection heat transfer inside the tank to the total rate of heat loss varies depending on the temperature profile inside the tank. At the beginning of standby mode, stored water inside a storage tank may be stratified, or 'well-mixed', depending on charging and discharging operations during the day.

Oliveski et al. (2003) conducted a study on transient cooling of well-mixed water in a cylindrical tank. Based on the findings, the authors developed correlations that can be used for estimating convection heat transfer coefficient inside the tank. However, the tank must be initially well-mixed to use the correlation. Furthermore, the correlation also poses limitations in its use since it was tied to a limited range of R-values for both the tank wall and insulation.

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To overcome the limitations from the study of Oliveski et al. (2003), Rodriguez et al. (2009) numerically investigated the cooling of a non-stratified cylindrical storage tank. The results were then presented in the form of a dimensionless correlation to predict convection heat transfer coefficient inside the tank. Although the correlation they developed was valid for a wider range of R-values of tank wall and insulation, it was still tied to the time elapsed from the initial non-stratified state of the tank at the beginning of standby mode.

Avoiding the issue of time-elapsed, Lin and Akins (1986) studied pseudo steady state natural convection inside a vertical cylinder by dynamically adjusting the wall temperature to maintain a constant temperature difference between the wall and the fluid following an instantaneous change of temperature of the cylinder wall. This boundary condition resembles the heating of a stratified storage tank They proposed a Nusselt number correlation, as a function of Rayleigh number, for different aspect ratios. However, the relationship is only valid for Rayleigh numbers (based on volumetric heat generation) of less than 10⁷, thus, limiting its applicability to solar domestic storage cylinders, where Rayleigh numbers are often three orders of magnitude higher than 10⁷.

Thus, there is a lack of generalized relationship that can predict convective heat transfer coefficient inside initially stratified tanks, based on the temperature difference between the stored water and the wall, independent of cooling time and R-values of tank insulation. Therefore, it is interesting to see if a combination of the well-established vertical flat plate correlation of Churchill and Chu (1975), as well as the upward facing horizontal plate and downward facing horizontal plate mentioned in Çengel (2007), would be able to predict the natural convection heat transfer coefficient inside cylindrical tanks for a given temperature difference between the wall and the water.

As such, this work aims to investigate the suitability of using existing flat plate correlations to estimate the natural convective heat transfer coefficient inside vertical cylindrical storage tanks, having different volumes and aspect ratios that fall within the range of solar domestic hot water tanks.

2. Methodology

To obtain steady state numerical results that can be compared with flat plate correlations, a computational fluid dynamics (CFD) approach was used. In doing this, a three-dimensional cylindrical tank with internal uniform heat generation was modelled using the CFD code, ANSYS Fluent 19.2. Two tanks, having aspect ratios between 1 and 3, and volumes of 169 L and 269 L, were considered since these fall within the typical range of solar domestic hot water cylinders. The rate of heat generation was adjusted to maintain an average water temperature of 60°C, while the insulated end walls and isothermal sidewall were held at a temperature (T_w) of 59°C, as shown in Figure 2.



Fig. 2: Schematic of the computational boundary conditions

In analysing the natural convection, the Rayleigh number (based on volumetric heat generation) can be defined as shown in equation (1).

$$Ra_Q = \frac{g\beta\rho c_p \dot{Q}_v H^5}{vk^2}$$
(eq. 1)

Where g is the acceleration due to gravity (m/s^2) , β is the volume expansion coefficient $(1/^{\circ}C)$, ρ is the density of fluid (kg/m^3) , c_p is the specific heat capacity of fluid (J/kgK), Q_v is the volumetric heat generation rate (W/m^3) , H is the height of the tank (m), v is the kinematic viscosity (m^2/s) , k is the thermal conductivity of fluid (W/mK).

On the other hand, Rayleigh number (based on temperature difference) is defined by equation (2).

$$Ra_T = \frac{g\beta(T_f - T_w)H^3}{v\alpha}$$
(eq. 2)

Given the cases analysed, the Rayleigh number (based on the temperature difference) lies in the range $10^{10} < Ra_T < 10^{11}$. Referring to Oliveski et al. (2003) and Rodriguez et al. (2009), the convective heat transfer coefficient on the sidewall for such cases is in the order of $10^2 W/m^2 K$. Taking this into consideration, the rate of volumetric heat generation required to keep the average temperature of water at 60°C are also in the order of $10^3 W/m^3$. Thus, the expected Rayleigh number (based on volumetric heat generation) will be in the order of $10^{13} < Ra_Q < 10^{14}$. Kulacki and Richards (1985) reported that the laminar regime can be obtained for $Ra_Q < 10^7$ in their numerical study on cooling of rectangular fluid layers with internal heat generation and insulated bottom wall. Solutions for cylindrical hot water tanks may also apply to rectangular hot water tanks provided that the condition in equation (3) is met.

$$D_c \ge \frac{35H_c}{\left(\frac{Ra_T}{Pr}\right)^{\frac{1}{4}}} \tag{eq. 3}$$

Where D_c is the diameter of the cylinder (m), H_c is the height of the cylinder (m), Pr is the Prandtl number of the fluid.

It was found that all the cases used in this study satisfy the criteria given in equation (3) and thus, turbulence modelling is needed since all the cases are expected to have $Ra_Q > 10^7$. For the treatment of turbulence in volumetrically heated enclosures, Dinh and Nourgaliev (1997) showed that reasonable results consistent with experimental data can be obtained using low-Reynolds (Re) number $k - \varepsilon$ turbulent models. Having said that, the low-Re turbulence model of Lam Bremhorst was used in this study.

A grid convergence index (GCI) with a safety factor of 3 was applied to perform a grid independence analysis, as reported by Roache (1998). The resulting GCIs between the coarse mesh (15 mm) and the fine mesh (7.5 mm), calculated based on the average temperature of the tank, showed a maximum error of 0.01%, indicating that a mesh with 15 mm cell size was adequate.

Given the temperature differences, the Boussinesq density model was used, this considers the density of water as a linear function of temperature only during the computation of body force in the momentum equation. The maximum error in density resulting from the Boussinesq approximation was found to be less than 0.002% in comparison to the non-Boussinesq data when using the thermal expansion coefficient of water evaluated at a reference temperature of 59.5°C.

To validate the computational methodology of modelling a cylindrical tank with volumetric heat generation, a threedimensional rectangular tank model was modelled and the resulting Nusselt number on each wall was compared with the experimental data of rectangular layer of fluid subjected to isothermal cold walls, as reported by Steinberner and Reineke (1978). Six validation points were chosen from the study of Steinberner and Reineke (1978) and the CFD tank models with different volumes with the same aspect ratio of 1 were developed to match the Rayleigh numbers of chosen validation points, as indicated in Table 1.

H (m)	AR	Volume (L)	$\dot{Q_V}(W/m^3)$	Ra_Q
0.5	1	125	2000	6.28×10^{12}
0.52	1	140	2000	7.64×10^{12}
0.55	1	157	2000	1.01×10^{13}
0.6	1	216	2000	1.56×10^{13}
0.63	1	250	2000	1.99×10^{13}
0.8	1	512	2000	6.58×10^{13}

Table 1. Chosen validation points along with dimensions of CFD models considered

From figure 3, it can be seen that the simulated CFD results agree reasonably well with the published data of Steinberner and Reineke (1978) for each tank wall, except the bottom wall which indicated differences of up to 55%. However, it is important to note that rate of heat loss through the bottom wall only contributes less than 6% of the total heat loss and thus, it is not likely to cause significant errors when predicting the rate of heat loss from the tank.



Fig. 3: Validation of CFD method with published Nusselt numbers on top, side and bottom walls from Steinberner and Reineke [6]

3. Results and Discussion

In considering the results in Figure 4 (a), it was apparent that increasing the aspect ratio of the tank led to a decrease in convective heat transfer coefficient on the side wall. This is associated with the degree of thermal stratification in the tank, which becomes more pronounced with increasing aspect ratio. The degree to which thermal stratification changes with aspect ratio can be represented by the maximum temperature difference of water inside the tank, as shown in Figure 5. It appears that this may suppress the buoyancy driven boundary layer flow, which leads to a lower convection heat transfer on the side wall. This relationship between aspect ratio and heat transfer agrees with the findings of Kulacki and Richards (1985) and Holzbecher and Steiff (1995) who investigated a similar case, but for laminar flows.

Unlike the sidewall, numerical simulations showed that the convective heat transfer coefficient on the top wall increased with increasing aspect ratio, as shown in Figure 4 (b). As the aspect ratio increases, water that is cooled by the top wall interacts with the boundary layer on the sidewall. This results in stronger convective cells close to the

top wall, which increase the natural convection heat transfer near the top wall. Conversely, on the bottom wall, no notable variations in convective heat transfer coefficient with aspect ratio was observed, as can be seen from Figure 4 (c). This is owing to weak natural convection on the bottom wall due to the small temperature difference between water in that region and the tank wall.



Fig. 4: Convection heat transfer coefficients on the (a) side, (b) top and (c) bottom tank walls, and (d) total rate of heat loss from storage tank models



Fig. 5: Maximum temperature difference of water inside the tank reflecting the degree of thermal stratification for tank models with different aspect ratios

From observation of the differences between the numerical results and those predicted from flat plate correlations in Figure 4 (a), it is worth noting that estimations of convective heat transfer coefficients from a vertical plate is the closest for the tank with an aspect ratio of 2.3 while noticeable deviations were observed for aspect ratios of 1 and 3 for tank models with higher volume of 269 L. High convection heat transfer in low aspect ratio tanks can be attributed to mixing inside the tank generated by the sinking motion of hot water upon losing heat to the top cold wall, as

illustrated in Figure 8 and 9. This phenomenon tends to be confined to the top region of the tank as the degree of thermal stratification increases with increasing aspect ratio, resulting in a low convective heat transfer coefficient. Though this effect is less pronounced in the tank model with a lower volume, of 169 L (see Figure 6 and 7).

Interestingly, the predicted heat transfer coefficients on the top wall, using flat plate correlations, are significantly lower than the numerical results, as shown in Figure 4 (b). This is associated with the formation of convective cells near the top section of the tank (see Figure 6-9) since the top wall is bounded by side walls to form an enclosure-like configuration, unlike the case of an isolated horizontal flat plate. Given the weak natural convection on the bottom wall, very little discrepancies between simulated and predicted results was observed, as can be seen from Figure 4 (c).



Fig. 6: Velocity contours inside 169L tank models (a) AR = 1, (b) AR = 2.3 and (c) AR = 2.8



Fig. 7: Temperature contours inside 169L tank models (a) AR = 1, (b) AR = 2.5 and (c) AR = 2.8



Fig. 8: Velocity contours inside 269L tank models (a) AR = 1, (b) AR = 2.3 and (c) AR = 2.8



Fig. 9: Velocity contours inside 269L tank models (a) AR = 1, (b) AR = 2.3 and (c) AR = 2.8

From the observation of the difference in overall rate of heat loss between numerical results and predictions from flat plate correlations in Figure 4 (d), it is apparent that the existing flat plate correlations cannot accurately estimate of rate of heat loss with the maximum deviation of 23% was observed for the case of 169L tank with aspect ratio of 1, owing to the discrepancies in convective heat transfer coefficients on the side and top walls.

4. Conclusion

Natural convection heat transfer inside cylindrical enclosures, which is applicable to stratified solar water storage tanks, has received little attention and because of this, there is a lack of relationships that can be used to determine the rate of heat loss from such systems. To address this, this study examined the suitability of using a combination of existing flat plate correlations to predict convective heat transfer coefficient inside stratified vertical cylindrical tanks with different volumes and aspect ratios that fall in the range of solar domestic hot water tanks. The results showed that there are discrepancies in convective heat transfer coefficients on the top and side walls between flat plate correlations and those of simulated data. This highlights the fact that there is still a need to develop a correlation that can predict convective heat transfer coefficient inside tanks independent of time elapsed from the initial non-stratified state of the tank and R-values of tank insulation.

5. Symbols and Abbreviations

Symbols		Subscripts		
AR	Aspect ratio	i, conv	Internal natural convection	
c_p	Specific heat capacity (J/kgK)	w,cond	Conduction (wall)	
Ď	Diameter (m)	ins, cond	Conduction (insulation)	
g	Gravitational acceleration (m/s^2)	e, conv	External natural convection	
h	Local convection heat transfer coefficient (W/m^2K)	f	Fluid (water)	
Η	Height (m)	env	Ambient	
k	Thermal conductivity (W/mK)	W	Wall	
Nu	Local Nusselt number	с	Cylinder	
Pr	Prandtl number	side	Side wall	
$\dot{Q_V}$	Rate of volumetric heat generation (W/m^3)	top	Top wall	
Q	Rate of heat loss (W)	btm	Bottom wall	
R	Thermal resistance (K/W)	loss	Heat loss	
Ra_Q	Rayleigh number (volumetric heat generation)			
Ra_T	Rayleigh number (temperature difference)			
Т	Temperature (° C)			
ΔT_f	Temperature difference of fluid within the tank ($^{\circ}C$)			

- β Volume expansion coefficient $(1/^{\circ}C)$
- v Kinematic viscosity (m/s^2)
- ρ Density (kg/m^3)

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A Thermal Model of a Solar Cooker with Thermal Energy Storage using Computational Fluid Dynamics

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Abstract

In this paper, a thermal model of a solar cooker with thermal energy storage (TES) cooking unit is developed. The solar cooker is a parabolic dish concentrating cooker. To allow cooking during hours with limited or no sunlight, thermal energy storage material is integrated in the cavities of the cooker. Sunflower oil is used both as thermal storage material and cooking fluid. As this oil is a fluid, computational fluid dynamics (CFD) was used to model the fluid flow and heat transfer within the solar cooker. The model was validated with experiments and comparison shows that the RMS error between experiments and simulations was around 2%. The fluctuating solar flux in the experiments was the main reason for this deviation. With the validated model, the physics of the charging of the TES and its interaction with the cooking pot is studied. During the beginning of the process, heat is transferred to the TES by conduction through the bottom and sidewalls. When the TES is heated up, the dominant heat transfer mechanism becomes natural convection, which transports the heat from the TES towards the cooking pot. This natural convection induces a fairly uniform temperature profile in both the TES and the cooking pot. With an incoming solar power of 4750 W m², a steady state temperature of 409.8K in the TES, and 405.8 K in the cooking pot can be reached within 4 hours. The maximum temperatures are very close to those observed in the experiments (410.9 K for the TES and 406.8 K for the cooking pot), and these temperatures are sufficiently high to cook or bake various food items.

Keywords: Solar Cooker, Thermal Energy Storage, Computational Fluid Dynamics,

1. Introduction

The use of solar cookers eliminates the usage of traditional fuels such as coal or wood and reduces greenhouse gas emissions. The most efficient type of solar cooker in terms of the shortest cooking time and the highest cooking temperature is the parabolic dish solar cooker. Cheap and efficient designs of parabolic dish solar cookers for developing countries have been investigated recently (Ahmed et al., 2020; Mohod et al., 2010). However, a major drawback of these solar cookers is that they cannot be used when the sunlight is limited or even not available, for instance at night or during cloudy periods. To cater for this drawback, thermal energy storage (TES) systems can be integrated with solar cookers so that off-sunshine cooking can be possible (Mbodji and Hajji, 2017; Mawire et al., 2020). The two main options for TES for solar cookers are indirectly storing the thermal energy in a storage tank using a heat transfer fluid (HTF) or storing the thermal energy directly in the cooking pot. The latter seems to be more economically viable since the use of fluid circulating pumps and pipes is eliminated. Plenty experimental studies have been performed to optimize the design of these solar cookers, to choose the most appropriate materials for the TES and to study the cooking performance (Vigneswaran et al., 2017; Wollele and Hassan, 2019; Mawire et al., 2020). Nevertheless, some of the authors have suggested the use of a numerical model for performance enhancement and optimization. In particular, experimentally validated computational fluid dynamics (CFD) tends to provide detailed insight of the fluid flow and heat transfer mechanisms. Studies on CFD models for cooking processes are rather limited (Joshi et al., 2012; Kumaresan et al., 2015; Mbodji and Hajji, 2017; Abreha et al., 2019), thus it is essential to develop models that can be used to enhance and optimize the performance of solar cooking storage pots that can be used for off-sunshine cooking hours. Therefore, the aim of the paper is to develop such a CFD model for a solar cooking storage pot for performance enhancement and optimization. The novel aspect of the study is the use of vegetable oil as TES, promoting a greener environment and a cheap sustainable cooking solution for developing countries. Few studies have appeared in recent literature on solar cooking pots using vegetable oils, and the results



Fig. 1: Photograph of the parabolic dish solar cooker with TES system implemented in the cooking pot. Left: parabolic solar collector, right: cooking pot with TES system

presented will provide invaluable information on the design and heat transfer mechanisms of these cooking pots. After model validation with experiments, a detailed study on the heat transfer characteristics and performance parameters is done, including the transient charging process of the TES and the steady state temperatures in both the TES and cooking pot.

2. Numerical model

The solar cooker used in this work is based on the parabolic dish solar cooker used in the study of Mawire et al. (2020). A photograph of this setup is shown in figure 1. The solar light is concentrated by a parabolic dish with a diameter of 1.2m and focussed on the bottom of a cooking pot. In this study, only the cooking pot with TES system is modelled and the parabolic collector is substituted by a solar heat flux input at the bottom of the pot. A schematic view of the pot geometry is shown in figure 2. The cooker is axisymmetric with the x-axis as symmetry line and the radius is $R_c = 0.16m$ and the height $H_c = 0.11m$. The cooker consists of two compartments: one for the thermal energy storage (TES) system on the bottom with a height H = 3.2cm and one for the cooking fluid in the middle (called the cooking pot) with a radius R = 0.125m. The walls of the cooker (represented by the thick black lines) are made of stainless steel and have a thickness of 3mm. For both compartments, sunflower oil is used as the heat transfer fluid. The volume of oil in the TES system is 3.75 liters and for cooking, a mass of 0.5 kg oil is used.

As both the TES and cooking pot consist of a mixture of oil and air, Computational Fluid Dynamics (CFD) is used to model the heat transfer and associated natural convection within both volumes. The equations governing the fluid flow are given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0, \qquad (\text{eq. 1})$$

for the continuity equation and

$$\rho(\frac{\partial \boldsymbol{V}}{\partial t} + \boldsymbol{V} \cdot \nabla \boldsymbol{V}) = -\nabla \mathbf{p} + \nabla \cdot \left(\mu(\nabla \boldsymbol{V} + (\nabla \boldsymbol{V})^T) - \frac{2}{3}\mu(\nabla \cdot \boldsymbol{V})\boldsymbol{I}\right) + \rho \boldsymbol{g}, \text{ (eq. 2)}$$

for the momentum equation, where ρ (kg m⁻³) is the density of the fluid, V (m/s) is the velocity vector, μ (kg m⁻¹ s⁻¹) the dynamic viscosity, p (Pa) the pressure, I the unity tensor and g (m s⁻²) the gravitational acceleration. In each compartment, a mixture of oil and air is present. To capture the free surface between them, the volume of fluid method is used (Hirt and Nichols, 1981). The material properties of the sunflower oil, like density, heat capacity, viscosity and thermal conductivity are temperature dependent and taken from the studies of Mawire et al. (2020), Fasina and Colley (2008), Cancaim (2012) and Hoffmann et al. (2018).

The boundary conditions are estimated from the work of Mawire et al. (2020). At the bottom of the cooker, a constant heat flux of 4950 W m^{-2} is applied, which corresponds to the average solar flux measured in the experiments. The



Fig. 2: Schematic view of the geometry of the solar cooker with a TES system. The X's denote the locations of the temperature measurements for validation

heat losses through the top and side walls are modelled as a combination of convective and radiation heat fluxes. The corresponding parameters are determined from the experiments, which give an average heat transfer coefficient $h = 26.5 \text{ W m}^{-2} \text{ K}^{-1}$. As the pot was painted black, the emissivity is chosen to be 1.

All governing equations for the gas and liquid phase were solved simultaneously using the pressure-based finitevolume solver ANSYS Fluent. For convective and diffusion terms, a second-order upwind discretization scheme was used. The PRESTO! interpolation scheme was adopted to obtain the pressure at the cell faces. The temporal derivative is discretized using a second order implicit scheme. A grid study using three different mesh sizes, coarse = 48.024 cells, medium = 216.512 cells and fine = 768.384 cells, shows that the results of the medium mesh are within 0.3% of the fine mesh and therefore the medium mesh is chosen in this study. To study the influence of the temporal discretization, 3 different timesteps (1, 0.5 and 0.25s) were adopted and the results of 0.5s where within 0.5% of the smallest time step and hence this timestep was chosen in the simulations.

3. Experimental validation

The numerical simulations are validated by thermocouple measurements at two locations in the cooker (denoted by the X's in figure 2) in the study of Mawire et al. (2020). Temperature measurements were taken every 30 seconds and the temperature evolution is shown in figure 3. Initially, the oil heats up very fast reaching a temperature of around 366K in the TES and 363K in the pot in the first hour. Afterwards, the temperature increase is slower and the varying experimental conditions have more influence on the temperature profile. Nevertheless, the CFD simulation is within measurement accuracy of the experiments for all timesteps. The RMS error between experiments and simulations was around 2%, and is mainly attributed to the fluctuating solar flux in the experiments. In the simulations, an average flux was implemented as boundary condition, which means that transient flux variations, like for instance found in the temperature decrease in figure 3 near the end, are not incorporated in the simulations. Hence, the CFD model is considered to be adequate in predicting the transient heat transfer in the cooking pot.



Fig. 3: Validation of the numerical simulations with the experiments of Mawire et al. (2020)

4. Heat transfer mechanisms

4.1 Transient heating

With the validated CFD model, the different heat transfer mechanisms can be studied in the heating process of the solar cooking pot. Figure 4 shows the temperature distribution in the cooker at different time instants. At the beginning, the bottom of the pot is heated by the solar radiation flux and this heat is transferred to the oil of the TES by conduction. The density and viscosity of the oil near the bottom decrease which creates buoyancy forces and less viscous resistance and hence hot oil is convected upwards. This induces Rayleigh-Bénard convection cells (figure 4a). These cells are the main heat transfer mechanism from the bottom of the cooker to the oil. Their regime is governed by the Rayleigh number, which is given by

$$Ra_L = \frac{g\beta}{\nu a} (T_b - T_u) H^3, \qquad (eq. 3)$$

where β (6.9858x10⁻⁴ K⁻¹) is the thermal expansion coefficient (Canciam, 2012), v (2.4854x10⁻⁵ m² s⁻²) the kinematic viscosity, α (8.5283 x 10⁻⁸ m² s⁻¹) the thermal diffusivity, T_b (330 K) the temperature of the bottom and T_u (281 K) the temperature of the top. The properties of the oil are taken at an initial temperature of 281K. At the start, the Rayleigh number is equal to 5.1913x10⁶. The Grasshoff number,

$$Gr = \frac{g\beta}{\nu^2} (T_b - T_u) H^3, \qquad (\text{eq. 4})$$

is equal to 1.7814x10⁴, which means that the natural convection is in the turbulent regime. As the oil heats up further, figure 4b, these Rayleigh-Bénard convection cells also appear in the oil in the cooking pot. As the temperature at the bottom of the cooking pot is lower, these convection cells are weaker than the ones in the TES. Due to convection, the oil on both the TES and cooking pot heat up quite uniform as shown in figures 4c and 4d.



Fig. 4: Temperature (K) profiles in the cooking pot at different time instants

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4.2 Steady state

The steady state temperature profile is shown in figure 5, and it is reached after about 4 hours. The average temperature at the bottom of the TES is 427.2 K and at the bottom of the cooking pot, it is 406.5 K. The average oil temperature in the TES is 409.8 K and the temperature distribution is very uniform due to the natural convection. Inside the cooking pot, the average temperature is 405.8 K and it is also very uniform. These temperatures are very close to the ones observed in the experiments (410.9 K for the TES and 406.8 K for the cooking pot) and are sufficiently high to cook or bake various food items.



Fig. 5: Steady state temperature profile

5. Conclusions

In this paper, a thermal model of a solar cooking pot has been developed and validated using computational fluid dynamics (CFD). Comparison with experiments shows that the resemblance between the two is within measurement accuracy and differences are attributed to solar flux variations in the experiments. With the numerical model, the physics in the heating of the cooker is studied. At the beginning, the main heat transfer mechanism is natural convection in the TES system, which creates a fairly uniform temperature profile. After 4 hours, a steady state temperature of 405.8K in the cooking pot is reached, which is sufficiently high to cook all sorts of food and vegetables. With the newly developed model in this study, solar cooking pots with integrated TES systems can be further optimized towards heat transfer, maximum temperature and warming up time.

6. Acknowledgments

The Interfaculty Council for Development Cooperation (IRO) of KU Leuven through the scholarship of Petros Tegenaw and VLIRUOS through grant number ZA2020SIN306A101 are gratefully acknowledged for funding this research.

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H-03. Domestic Solar Water Heating and Combisystems, Innovative Components and/or Materials

Performance comparison of different types of solar thermal collectors on residential space heating demand in high-altitude cold climatic environment: A simulation-based study

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Abstract

On the one hand, high-altitude rural Kyrgyz houses have a high heat demand, especially due to the age of buildings and low temperatures in winter evoked by the cold climate. On the other hand, this continental climate results in a high amount of solar irradiation over the year which is ideal for the application of solar systems and in particular solar thermal systems for heat energy supply. This study investigates the performance of different types of solar thermal collectors by considering the challenges for a solar thermal system in the harsh climate of Kyrgyzstan such as three different flat plate collectors and two evacuated tube collectors. For in-depth assessment, a parametric study on appropriate collector types was performed which helps to select the potentially most technoeconomically suitable combination of system components based on energy output, system security and economic feasibility. Unfortunately, under current circumstances, a solar thermal system is not economically feasible in rural Kyrgyzstan. The main two reasons are low energy prices for conventional heat sources and the lack of market for solar thermal applications.

Keywords: cold climate, solar thermal energy, solar thermal collector, high-altitude, domestic space heating, parametric study, techno-economic analysis

1. Introduction

1.1. The climatic situation of Kyrgyzstan

Kyrgyzstan is a former Soviet Union country situated in Central Asia and home to 6.5 million people (National Statistical Committee of the Kyrgyz Republic, 2020). The average altitude of the country is 2,800 m above sea level (CIA, 2021) which leads to cold climatic conditions. For example, in January the average temperature in Naryn, a city 2,000 m above sea level in central Kyrgyzstan, is -14 °C (Mehta et al., 2021). Depending on the region, this cold climate results in an extended winter period up to nine months. Because of the cold climate and extended heating season, domestic space heating is a key energy need for Kyrgyz people.

1.2. Theory and Context: Space Heating in rural Kyrgyzstan

Domestic space heating remains a key challenge for rural Kyrgyzstan where more than 65 % of the Kyrgyz population lives. The majority of the rural Kyrgyz building stock was built from earthen materials without proper building construction techniques during the Soviet era 30-50 years ago (Schweinichen et al., 2010; Mehta et al., 2020a). In addition, typical rural residential homes are one-story buildings built with poor or without insulation material. This results in a high heat flow rate out of the building (through the building envelope) which needs to be compensated by a heat energy supply equal to these losses to maintain the target temperature inside the building. These factors lead to a high domestic space heating demand in rural Kyrgyz households which is significantly higher compared to energy demand for cooking as well as for domestic hot water preparation. This high heat demand is usually covered by burning locally available non-sustainable solid fuels like coal, wood from neighboring forests, and dried cow dung from their livestock (Mehta et al., 2020a). District heating systems do not exist in rural areas, mainly due to too low heat density. Fig. 1 shows a typical rural Kyrgyz house and a traditional stove. Utilizing an excessive amount of solid fuels in low thermal efficient traditional stoves results in significant indoor and outdoor air pollution. Besides, the over usage of firewood leads to a negative impact on the riparian forests in Kyrgyzstan (Lauermann et al., 2020). Hence, there is a necessity to provide an approach that

helps to reduce solid fuel consumption and deliver sustainable heat for high-altitude house heating. The own comparative assessment indicated that the annual global irradiation of Kyrgyzstan is 60 % higher than a location in Central Europe (Mehta et al., 2020b). Accordingly, the potential of heat generated from solar energy is proportionally higher, which can be used to supply Kyrgyz households with sustainable heat. However, most of the solar energy remains untapped due to the lack of technical knowledge and infrastructure.

Nevertheless, the existing systems (for example a 0.5 MW system for the district heating network in Bishkek (Solar District Heating (Ed.), 2018)) are located in cities and are often used in district heating networks.



Fig. 1: Typical rural residential house in Kyrgyzstan with an open-roof construction (left) as well as a traditional heating stove (right) which is used for cooking and heating up one or two rooms of the building

2. Research objective and methodology

There is a lack of research available that focuses on solar thermal assisted heat supply systems and their usage in Kyrgyzstan, in particular for single-family households which is the most common form of living in rural areas (Schweinichen et al., 2010). Additionally, there is a gap in research regarding suitable collector types, the performance evaluation of solar thermal collectors in high-altitude and the extreme winters of Kyrgyzstan. Considering the lack of a heating concept based on solar thermal energy for households, there is a need to analyze possible concepts. To fill the gap of knowledge, the presented article deals with untapped solar thermal energy to perform the comparative assessment on residential space heating demand of high-altitude single-family rural Kyrgyz houses. The flowchart (c.f. Fig. 2) shows the methodology of this paper to compare the different types of solar thermal collectors and identify the best suitable configuration to tackle this problem. In a first step, the heat demand of residential households in cold-climatic and high-altitude Kyrgyzstan is identified. This results in a heat



Fig. 2: Methodology to identify the suitable solar thermal system for a residential house in cold-climatic and high-altitude Kyrgyzstan

load profile which will be subsequently used to create a heat supply model in *Polysun* (Vela Solaris AG, 2021). A parametric study with different types of collectors and system sizes will be used to identify suitable system configurations. The aim is to identify the technical suitability as well as the economic practicability of the selected collector types. By varying the type of collector, the surface area of collectors and the size of storage tank within a reasonable range, an optimized system configuration will be examined. As an outcome, this research aims to deliver a technical blueprint for the most suitable solar thermal assisted heat energy supply system from an economic perspective in rural Kyrgyzstan.

3. Simulations with different solar thermal collectors according to local conditions

3.1. Determination of heat demand of residential house

To evaluate the performance of the various configurations of solar thermal collectors and their contribution to the overall domestic space heating demand, the heat demand for a typical rural Kyrgyz house was identified. The simulation study was performed in *Polysun* software (Vela Solaris AG, 2021).

As mentioned previously, most of the high-altitude rural Kyrgyz homes are aged and without any insulation. These measures yield high heat demand. Mehta et al. (2020a) calculated the annual specific heat demand by simulation of a single-family house in rural Kyrgyzstan for space heating. Depending on the exact configuration of the investigated houses, the annual specific heat demand was at least 300 kWh/m².

For the presented research, the heat demand of a building is determined by the balance of heat gains (i.e., solar gains and internal gains) and heat losses (i.e., heat losses through building envelope). As radiation from the sun enters the building through the windows the interior of the building heats up. Therefore, the window area on every surface of the building is important. Other sources are people or electric devices, as they emit a small amount of heat. The internal gains of the here used standardized building accumulate up to 4,000 kWh/a (i.e. 1,000 kWh per year and inhabitant). Losses of the building are made up of infiltration and ventilation (involuntary and voluntary exchange of the warm air inside the building with air from outside the building) as well as the losses through the envelope of the building. The losses through the envelope correspond to more than three-quarters of all losses and are in cold climatic zones during winter always higher than the gains. To maintain temperature inside of the building an additional heat source is needed to cover the difference between gains and losses.

Focusing on heat losses through the envelope, a few parameters are necessary to properly determine the losses (in brackets the values used in this study can be found):

- Heating set point of the building (20 °C during the day, 19 °C during night; see also Botpaev et al., 2011)
- Average outdoor temperature (weather profile provided from the integrated Meteonorm Webservice in *Polysun*)
- U-value of the building (calculation based on the proportional U-values and areas according to Mehta et al., 2020a and Botpaev et al., 2008: 1.2 W/m²K for the whole building, in software *Polysun* there is no distinction between U-values of different building components)

The software *Polysun* provides hourly values (or even shorter intervals) for heat demand which is necessary to analyze the dynamic performance of the solar thermal system efficiency. The calculated hourly heat demand and the outdoor temperature are displayed in Fig. 3. In this figure domestic hot water demand (DHW) with around 1950 kWh/a is excluded because it is negligibly small compared to the demand for space heating. There is an inversely proportional correlation between the low temperatures during the winter months and the corresponding heat demand during these months. Due to the temperature difference, the losses through envelope are the main drivers for heat demand in this case. Correspondingly to the outdoor temperature, the heating period lasts at least from October to the beginning of May.

The location of the system is $41^{\circ}24'47''$ N, $75^{\circ}03'16''$ E in the Naryn region, Kyrgyzstan. The building size is 10 m x 10 m x 2.5 m. Window-to-wall area ratios are 6 % for the north, 13 % for the west, 25 % for the east, 25 % for the south. Using these parameters (including values for losses) results in a heat demand of 367 kWh/m²a. Compared to German standards where according to Deutsche Energie-Agentur GmbH, 2016, 90 % of the houses have a lower heat demand, this is a high heat demand. To cover such high demand and always guarantee an availability of enough heat, it is necessary to combine a solar thermal system with another heat source like a boiler, stove, or heat pump, as these devices can provide energy independently from solar irradiation. Theoretically, seasonal storages for solar thermal systems can solve this problem. However, they are typically not affordable for the rural population as the necessary investments would be enormous (Yang et al., 2021).

Additionally, from this diagram (c.f. Fig. 3) the necessary size of the heat supply system can be derived. This is done by analyzing the peak energy demand over the whole year. In this case, the maximum power is just above 20 kW at around mid of January. As the reference system only uses one heat source, this supply unit should be sized in a way, that it can cover the total heat demand. This is necessary to avoid any deficits as they would lead to the lower temperature inside of the building which relates to less thermal comfort. But as "[...] oversizing does not influence the indoor thermal comfort, but [only] leads to increase of primary energy consumption [...]" (Peeters et al., 2007), it may be advisable to select a boiler in the size range around 22 to 25 kW to guarantee to produce enough heat for the building.



Fig. 3: Simulation results show a typical heat demand profile for the given continental climate conditions in the northern hemisphere (in this case: rural residential house in high-altitude Kyrgyzstan around 1,500 m above sea level which results in a heat demand of 367 kWh/m²a). The location of the system is 41°24'47" N, 75°03'16" E in the Naryn region, Kyrgyzstan.

3.2. Overview of different collector technologies

There are various types of collectors available to generate heat for space heating or DHW purposes. In this study, four different technologies are selected (c.f. Tab. 1). The goal is to identify the best-performing collector by selecting the system with the biggest potential in energy savings combined with acceptable economic feasibility. The following information provides a brief overview of the five selected cases (information from Sam, 2011; Kaltschmitt et al., 2014; Evangelisti et al., 2019; Ehrenwirth, 2021).

Case 1 is a simple unglazed flat plate collector. This type of collector is not insulated and does not have a glass cover at the front. They often consist of black plastic material and are used in low-temperature applications. According to Evangelisti et al. this collector has its best performance below a target temperature of 30 °C. Cases 2 and 3 are flat plate collectors (FPC) which are the most common collectors for solar thermal applications and especially DHW preparation as they are suited for target temperatures in the range of 20 to 80 °C (Sam, 2011). In comparison to the unglazed flat plate collectors, heat is trapped at the absorber due to insulation at the back and a front glass pane which allows reaching higher temperature levels.

The evacuated tube collectors (ETC) use additional insulation technologies to optimize heat flow. Case 4 and case 5 fall under this category of collectors as they both have vacuum chambers which increase the insulation of the fluid to the surroundings. So, less heat is lost. Consequently, this relates to a reduced aperture area. Case 5 uses heat pipes, a more complex technology. Within these pipes, a second trapped fluid is heated up. Due to the conditions, steam is generated which starts to circulate in the tube. This steam condenses when it gets in contact with the solar cycle fluid at the top of the collector. During this condensation, heat is conducted to the solar fluid.

	Case 1	Case 2	Case 3	Case 4	Case 5
Type of collector	Flat plate collector, unglazed	Flat plate collector, inexpensive	Flat plate collector, good quality (FPC)	Evacuated tube collector in u-shape (ETC)	Evacuated tube collector with heat pipe risers
Gross area in m ² per collector	1.28	2	2	2	2.42
Aperture area in m ² per collector	1.28	1.8	1.8	1.4	1.4
ηο	0.77	0.70	0.80	0.70	0.73
a_1 in W/(m ² K)	13.13	4.00	3.50	2.10	1.45
a_2 in W/(m ² K ²)	0.85	0.03	0.02	0.01	0.02
Yield in kWh per m ² gross area and year *	4	400	550	530	580
Costs in € per m ² **	100 (Tackmann, 2019)	200 ***	300 (Ehrenwirth, 2021)	600 (Kloth, 2018)	800 ***

 Tab. 1: Comparison of collectors and their parameters used for this study based on *Polysun* catalogue/database (type of collector equals name form database; Vela Solaris AG, 2021)

* = Yield is calculated by counting the heat energy available at a temperature level of 66 °C (65 °C target temperature for the distribution system and 1 °C cut-in difference necessary for controlling the system). The location of the system is $41^{\circ}24'47''$ N, $75^{\circ}03'16''$ E in the Naryn region, Kyrgyzstan.

** = The costs only include the price for the collector and the necessary components to mount them on the roof of a building (metal sheet roofing). Additional installations costs for storage tank and infrastructure are not part of this.

*** = Own estimations according to literature sources which often state a price range for one collector technology. Here, e.g., cases 2 and 3 are FPCs in two different price ranges according to their given performance parameters.

3.3. Simulation Model in Polysun

In the software Polysun (Vela Solaris AG, 2021) a model of the whole heating system was set up (c.f. Fig. 4). This software program helps to analyze the efficiency and performance of the system components. The model includes a building (1) according to the descriptions above in chapter 3.1, representing a heat demand profile. To fulfil this demand, a supply and distribution system is necessary (components 2 to 8). To heat up the building radiators with a constant fluid inlet temperature of 65 °C (2) are used which emit heat to the surrounded area (volume inside the building). This results in a return flow with lower temperature. To ensure that the temperature of the radiator holds its desired level, a mixer (3) is installed which controls the inlet flow. This component mixes the hot water from storage tank (6) with the colder water of the return flow to establish a constant fluid temperature at the inlet of the space heating system. This is necessary as the temperature in the top layer of the storage tank (6) is not constant as this depends on the top layer temperature of the storage tank and the productivity of the two heat generation units (7 and 8). The biggest share of the necessary heat is provided by a boiler (7) which is dimensioned (see also Ch. 3.1) in such a way that the system can be operated with the boiler only. This design allows comparing the heat supply system with a reference layout that does not include the application of solar thermal collectors. In this study, the heater can provide 25 kW for the fluid which is fed to the storage tank. The boiler is running in case the temperature in the upper third of the storage tank drops below the inlet temperature setting for the space heating system (2), in this case, 65 °C. Additionally, to provide DHW (5) the system includes a heat exchanger inside of the storage tank and a mixer to provide hot water at the set temperature of 50 °C for 100 liters/day equally distributed over the day.



Fig. 4: System layout of the model used for simulations in this study. Main components are the building (1), heat distribution system (2), mixer for space heating (3), cold water source (4), domestic hot water system (5), storage tank (6), boiler/stove (7) and solar thermal system (8).

On the left side of the system layout, the solar thermal system (8), is displayed. A simple system configuration with a closed glycol-mixture loop with 40 % glycol and 60 % water together with a heat exchanger inside of the storage tank is used. Heat can be transported into the storage tank in case the collector temperature is higher than the layer temperature at the upper end of the internal heat exchanger. In the presented study, the modules of the solar thermal system are oriented to the south with a tilt angle of 45° .

Own evaluations showed an optimum yield of energy from the solar thermal system when using a tilt angle of a little bit more than 60°. However, according to own assessments, most of the roofs in the rural Kyrgyz region are less steep. This would require a special substructure for elevating the collectors. Then, the tilt angle can be increased compared to the roof angle. This measure would increase the heat output of the solar thermal system but will increase costs. Additionally, the complexity in planning the system will be increased, e.g. due to carefully planning the substructure's ability to resist wind and snow loads. Currently, no such detailed weather data for rural Kyrgyzstan is existing. This makes a case-by-case calculation necessary to guarantee to avoid any problems from the possible extra load on the roof.

The described model was used to perform different simulations of various collector configurations. This includes a parametric study where every case of collector type is selected and simulations with a number of collectors from 1 to 10 are performed. Collector yield and costs are compared in relation to the occupied surface.

4. Techno-economic assessment of parametric study

In a first step, the efficiency of the different solar thermal systems is analyzed. This includes an analysis of the heat production of the solar thermal system (see Fig. 5 left) and an evaluation of fuel consumption of the boiler (c.f. Fig. 5 right). In both diagrams, the green diamond represents the reference system. On the one hand, as this reference model does not have solar thermal included the heat production from this source is 0. On the other hand, this system has the highest fuel consumption with 52.1 MWh.



Fig. 5: Trend of solar thermal heat production (left) and the corresponding fuel consumption for different solar thermal system configurations (right)

In comparison with the reference system, the benefits of installing unglazed collectors (case 1) are negligible. The yield of the collector is insufficient as the necessary target temperature to feed the storage tank is only reached for a few hours during the year. This allows only for little savings in fuel consumption of around 300 kWh per year.

The other four collector types show a behavior which is similar among themselves as they all trend comparably. When increasing the system size, it can be recognized that due to the lower efficiency of inexpensive flat plate collectors the solar heat production per gross area of collectors is lower than using more efficient collectors. This result was expected.

The advantages of evacuated tube collectors (case 4 and case 5) are insignificant. The temperature levels required within the system are typical for a standard residential house and far below 80 °C. However, this is the temperature level ETCs are made for (Evangelisti et al., 2019). Additionally, it must be considered, that the solar thermal system feeds the storage tank in its lower third (c.f. Fig. 4). Typically, temperatures are low in the lower part of the storage tank due to layering processes inside the tank (Sterner and Stadler, 2016). So, filling the storage tank with higher temperature differences which is more often the case for ETCs can be less efficient due to circulation related from the mixing processes inside the storage tank. Another small contribution to a worse performance is higher standing losses due to higher temperatures for a longer period of time.

Nevertheless, all systems show a decrease in fuel consumption which is comparatively low to total demand, as even the best configurations can reduce fuel demand by only about 12 %. This is due to the higher heat demand during winter times where the solar thermal system is less effective, so the contribution to a reduction of heat demand is low. Demand for space heating during summer is negligible as temperatures don't drop to levels below 15 °C for longer periods. DHW demand is nearly fully covered by solar thermal energy.

The inconsistent trend which is particularly evident for both ETCs can be explained by considering the settings for controlling the pump in the solar thermal loop. In this study, all simulations are performed with a flow rate of 40 l/h per m² aperture area. Consequently, when changing the gross area of collectors by varying the number of collectors also flow rate changes which again influences temperature level in the collectors and runtime of the

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system. All factors influence the solar thermal yield. In this study, increasing the gross area relates always to an increase in solar thermal yield (c.f. Fig. 5). The correlation between flow rate and solar thermal yield is more complex. Here for most system configuration the assumption of 40 l/h per m^2 is a suitable approximation to generate a maximum in solar yield. However, for specific system configurations, the ideal flow rate configuration differs from 40 l/h per m^2 .

For instance, this situation can be identified when considering a serial system consisting of four ETCs with heat pipe risers (case 5). According to the value of 40 l/h per m² aperture area, this system configuration uses a flow rate of around 220 l/h. But when performing a simulation for the identical system with a slightly adjusted flow rate of 200 l/h, the system configuration can manage to provide around 250 kWh more solar yield (which equals around 7 % more yield compared to the system used in this study). Due to the lower flow rate, higher temperatures in the collector can be reached. Especially during summer times it is relevant as the storage tank is often charged and higher temperatures are necessary to transfer heat into the system.

Finding the best settings for each configuration needs to be investigated in further studies.

In a second step, an economic assessment is performed by considering the Levelized cost of heat for the different system configurations. The Levelized cost of heat (LCoH) is a parameter that assesses the costs of heat produced by the various (solar) thermal energy technologies (Ravi Kumar et al., 2021). The LCoH is calculated as following (adaption of calculation according to VDI 6002, 2014 as running costs are not considered here due to a small electricity demand of the system and the low electricity tariffs which sum up to less than $10 \notin$ per year):

$$LCoH \left(in\frac{\epsilon - ct}{kWh}\right) = \frac{[Costs of collectors (in \epsilon) + Installation costs (in \epsilon)] \times f_{a}}{fuel savings compared to reference system (in kWh)} \times 100 \frac{Ct}{\epsilon}$$
(eq. 1)

with annuity factor, fa = 6.72 % (considering system operation time of 20 years and capital market rate of 3 %).

The following bullet points will describe the parameters necessary to calculate the LOCH. An example using four collectors of case 3 (Flat plate collector, good quality according to collector name in *Polysun*) is included.

Costs of collectors

The prices for different types of collectors (cases) are stated in the Tab. 1. The price is given per gross collector area. This allows comparing the different cases.

Example: Four collectors of case 3 are used. Specific costs for this collector are $300 \text{ } \text{e/m^2}$. As each collector is $2 \text{ } \text{m^2}$ in size, the total costs for collectors are

$$\left(4 \times 2 \text{ m}^2 \times 300 \frac{\epsilon}{\text{m}^2}\right) = 2400 \text{ €.}$$
(eq. 2)

<u>Installation costs</u>

For installation cost it is assumed that the general installation cost is $2,500 \notin$. When installing a solar thermal system, a part of the installation costs is independent of system size. This includes planning the system, bringing material and workers to the construction site, implementing a storage tank. As this technology only barely exists in Kyrgyzstan, costs for installation are not available. So, assumptions are necessary for this context. The costs for the heat distribution system are not considered in this study.

Additionally, a small portion of the costs is depending on system size. This includes mounting each collector on the roof and plumbing. So, costs of $75 \text{ } \text{e/m}^2$ of collector area are assumed for this process.

The result for total installation costs equals values from literature (Kasper and Heidler, 2011; Kaltschmitt et al., 2014; Ehrenwirth, 2021).

Example: The installation costs for the selected system is

$$2,500 \notin \left(4 \times 2 \text{ m}^2 \times 75 \frac{\epsilon}{\text{m}^2}\right) = 3,100 \notin.$$
 (eq. 3)

• Fuel savings compared to the reference system

The annual yield of the solar thermal system equals not exactly the savings of fuel consumption. This is mainly due to storage tank losses (the storage tank constantly emits heat as it is not perfectly insulated).

By increasing the number of collectors this difference increases as the probability of a full storage increases. In other words: the same storage (considering the volume size) is charged faster with a bigger supply unit. This difference between fuel savings and yield from the solar thermal system in most cases is around 200 kWh. In relation to total demand, this is negligible, but considering the annual yield, it is a not inconsiderable proportion. Nevertheless, from an economical perspective, the fuel savings are relevant as this is the amount of energy difference seen on the bill for fuel. LCoH is calculated accordingly.

Example: According to the simulation results from *Polysun*, this system configuration yields a reduction in fuel consumption of 4,224 kWh/a.

These parameters can now be applied to eq. 1.

Example: For the selected system the result is following:

$$LCoH = \frac{[2400 \ \epsilon + 3100 \ \epsilon] \times 6.72 \ \%}{4,224 \ kWh} \times 100 \ \frac{ct}{\epsilon} = 8.8 \ \frac{ct}{kWh}$$
(eq. 4)

LCoH for all cases and every system size is calculated according to this method. As a result, a graph is drawn (c.f. Fig. 6) which shows the development of the LCoH plotted over the gross area of collectors.



Fig. 6: Trend of Levelized costs of heat for different solar thermal system configurations

As already described above the fuels savings by using unglazed collectors are less than 300 kWh per year, even for the biggest system configuration of this study. This makes the unglazed collector economically not feasible (see also in Tab. 1 in line 4) as LCoH is around 80 €-Ct/kWh or more. Adding graph for case 1 to this graph would strongly distort it.

Focusing now on the four other cases LCoH of heat between 9 and $16 \notin Ct/kWh$ can be reached. The best system configurations from an economic point of view range between 5 to 10 m^2 of gross collector area. As the flat plate collectors are in a similar range of fuel savings compared to the ETCs, their lower specific costs (in \notin/m^2) become more relevant yielding lower LCoH. Both FPCs do follow the same trend (additional fuel savings from Case 3 collector directly correspond with the higher investment). The inconsistent trend can be seen here too. But as FPCs are the economically more suitable solution the deviation in the curves is not significant.

Unfortunately, estimating costs for one kWh from conventional energy production is difficult, especially for the rural Kyrgyz region due to a lack of information. Nevertheless, for urban areas approximations for the LCoH exist. Around 0.065 US\$/kWh_{th} are stated for a house boiler powered with coal for an individual household in the urban environment (Balabanyan et al., 2015). This equals around $5.5 \notin$ -Ct/kWh_{th}. It is possible that these LCoH

are higher compared to rural regions due to the unequally split of wealth in the country (Sultanov et al., 2020). In absence of any more precise data, $5.5 \notin -Ct/kWh$ is considered as a price in rural areas (green diamond in Fig. 6).

Bringing the trends of LCoH for solar thermal systems now in context with the costs per kWh using the conventional heating system, it needs to be stated that over a runtime period of 20 years the solar thermal systems are not competitive from an economic point of view as LCoH is always higher than the price for existing reference systems.

5. Discussion

5.1. Best system configuration from this parametric study

This parametric study showed the economic potential of solar thermal systems for rural Kyrgyz residential houses. Using system sizes which are common for single residential houses (up to 20 m²) fuel demand can be reduced by up to 12 % compared to a reference design based on conventional heat generation. As heat demand during the summer month is negligible and irradiation during winter is less, small systems are more effective as most of the heat produced can be used in the system. As a result, with small systems 500-650 kWh/m² (gross collector area) and for bigger systems around 300 kWh/m² fuel can be saved. In this study, the economically most feasible system uses four collectors from case 3. LCoH for this system is 8.8 \in -ct/kWh. With this solar thermal system, the annual fuel consumption can be reduced by 4,224 kWh which equals a decrease of fuel demand of 8.1 %.

All configurations show no problems regarding stagnation, even though the remaining capacity of the storage tank often is quite small. As there is still a small daily amount of DHW and the maximum stagnation temperature the collectors can withstand is (except for the case 1 - unglazed collector) above 200 °C, an overheating of the pressurized system with potential damage (Quiles et al., 2014) can be avoided. During the nighttime, the colder ambient temperature allows the collectors to cool down that far that on the following day overheating issues can be avoided.

Currently, no system analyzed in the framework of this study is economically feasible compared to the costs for an individual heating system based on conventional fuels which are about 5.5 e-Ct/kWh. Considering a runtime of 20 years, LCoH is always above the value for the conventional heat supply system. Even in case of neglecting interest rates, the cheapest system only reaches 6.5 e-Ct/kWh considering the assumptions for costs made in this study¹. But there are several ideas to make a solar thermal system more suitable from an economic point of view, especially as the difference of LCoH to the conventional system is small.

First, in this study, typical standard system configurations were analyzed. A heat distribution system is used based on a fluid cycle. As currently no market and know-how for such a solar thermal system exists in Kyrgyzstan, prices for such a system are high. Alternative systems which are less complex should be identified. Systems which are simpler and easier to install can be part of a solution. Systems like solar air collectors or direct heat exchangers without any storage tank do not require that much technical understanding during installation process, especially regarding setup of the piping and control units. These might be more appropriate solutions for the conditions prevailing on site and need to be investigated in the future.

Secondly, components and installation of them such as storage tank and distributions system are included in the LCoH for the solar thermal system. These measures, especially the distribution system, will drastically increase thermal comfort and living conditions. This point of view might relativize the strict economic analysis.

Third, there are political ideas to increase the economic potential of this technology whose technical potential is enormous (Mehta et al., 2020b). Possible measures are described consequently.

¹ In this study, the costs for importing the components and bringing the specialists from foreign countries to the construction site have not even been considered.

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5.2. Hurdles that need to be overcome to implement solar heating technology on a large scale

To make solar thermal technology widely acceptable, it is necessary to gear up the solar market in Kyrgyzstan. Such an opportunity will allow manufacturing of solar thermal products within the country with the available resources. Further to this, with the capacity building and knowledge dissemination, skilled manpower will be available who can install typical solar thermal heating technology in Kyrgyzstan. Such factors are the key drivers and can substantially reduce the capital cost of solar thermal-assisted heating technology. As a result, Levelized Costs for solar thermal applications will shrink too.

In addition to that, subsidies can help to make this technology more competitive and widespread. For example, the installation itself can be funded (e.g., by paying bonuses to the house owner when deciding to put solar thermal collectors onto their roof). This measure will happen very unlikely due to the politically and economically instable situation (Ismailov et al., 2021).

From an environmental point of view, it needs to be stated, that reducing heat demand from the building by optimizing the outer shell is more effective and economically feasible after shorter time periods. Previous research showed that insulation can reduce fuel consumption more efficiently as a lower investment is necessary (Beringer et al., 2021). Although, insulating a house is more relevant in case a new building or a big renovation is planned, whereas collectors can be installed on the roof of a finished house in case a heat distribution system is existing.

Finally, the financial situation, the existing heating situation in most of the households, and the lack of knowledge about the availability of such technologies currently don't allow the installation of solar thermal systems. Solving these issues is a complex task. But creating the awareness and ability to use renewable energy can help residents in aspects like healthcare and energy security by using local fuels and renewables. As a benefit, this is also contributing to a reduction of greenhouse gases globally. This helps to preserve Kyrgyzstan as a habitat for many different peoples and cultures.

6. Acknowledgments

The work presented in this paper was funded by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany within the CLIENT II funding program (International Partnerships for Sustainable Innovations) for the project "ÖkoFlussPlan" (Project ID 01LZ1802A-F). The overall aim of ÖkoFlussPlan is to preserve the alluvial forests along the Naryn river and to implement sustainable energy solutions for the local population.

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Energetic Comparison of Different Instantaneous Water Heater Concepts in a Solar Combi-System for a Multi-Family House with TRNSYS

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Abstract

In order to avoid heating the entire storage to 60 °C to fulfill the hygienic regulations, the use of central instantaneous water heaters (IWH) in multi-family houses is advisable. The cold preheating zone enables temperature-sensitive regenerative heat generators to provide part of the required energy at a lower temperature level as part of a bivalent system. In this work, the influence of the circulation loss of the building and the technical properties of the IWH on the CO₂ emissions, the solar utilization ratio and the solar fraction of a bivalent system with solar thermal and gas boiler is investigated. For this purpose, the heat transfer capability of the IWH and, if available, the actuating time of the return flow diversion are varied in a broad range. These parameters are based on a market analysis and own laboratory tests. With constant tapping profile and constant collector area, the circulation load has the largest impact on CO₂ savings, but technical characteristics also significantly affect CO₂ savings (+/-12 %). This is due to the fact that a high heat exchange rate lowers both the required maximum storage temperature (-10 K) and the resulting return temperature. With a short actuating time of the return flow diversion, low return temperatures lead to low temperatures in the lower storage, which can be efficiently heated by the solar thermal system. For a multi-family house with 1 kW circulation losses, CO₂ savings of (36 - 48 %) can thus be achieved, depending on the IWH.

Keywords: instantaneous water heater, solar combi system, solar thermal, UA-value, return diverter, TRNSYS simulation, efficiency

1. Introduction

The final energy consumption (FEC) in Germany has remained almost unchanged over the last 10 years at 9000 PJ/a, which corresponds to a per capita consumption of about 30 MWh/a.

The heating sector accounts for just over half of the final energy consumption, with space heating and potable hot water consumption in the residential sector accounting for almost one-third of final energy consumption. The share of potable water heating is constant at around 5% of the FEC, while energy consumption for space heating is declining due to renovation measures and milder temperatures as a result of climate change (AGEB e.V., 2019). Of the approximately 36 million metric tons of CO_2 generated by domestic water heating, the residential sector accounts for the lion's share (3.9 % of the FEC) (cf. Fig. 1). In 2018, around 60% of the residential sector in Germany was made up of multi-family houses, which therefore account for a large proportion of these emissions (Statistisches Bundesamt, 2019)).



Fig. 1: Distribution of the German final energy consumption 2018 for different sectors and analysis of the domestic hot water sector (data from (AGEB e.V., 2019))

Modernization and renovation of the building stock not only reduces the energy required for space heating, but also the correspondent supply temperature level. The focus of science has been therefore shifted to the heating of potable water, as this is responsible for the maximum required temperature. Especially in large systems, hygienic operation rules are an obstacle for temperature-sensitive heat generators such as heat pumps and solar thermal (Pärisch et al., 2020b), but also for district heating based on renewable energies. Central instantaneous water heaters offer hygienic advantages due to less stagnant water (Rühling et al., 2018). The use of a buffer storage also leads to energy benefits, since the creation of a cold preheating zone can increase the efficiency of temperature-sensitive heat generators (Pärisch et al., 2020a). In order to benefit from these advantages, this paper investigates the technical properties of IWH through a parameter study with the simulation program TRNSYS to determine their influence on the efficiency of a solar combi system in a typical multi-family house. The work in this paper continues the previous investigation by Pärisch et al., (2020b) and extends it with a broader variety of parameters.

2. Solar thermal combi systems with instantaneous water heater

Solar thermal combi systems consist of solar thermal collectors and an auxiliary heating system, usually a gas boiler, but systems with an electric heater or heat pump are also conceivable. There are two possibilities for the supply of domestic hot water (DHW) by a solar thermal combi system (VDI, 2014). On the one hand, the DHW can be stored directly in a storage, on the other hand the (solar) energy is temporarily stored in a smaller buffer storage and the DHW is heated as required/on demand. Particularly in large-scale systems, the first option would require a very large quantity of DHW to be stored and heated completely to 60°C once a day to fulfill the hygienic requirements (DVGW e.V., 2004). In order to keep the stored amount of DHW as small as possible, a buffer storage is therefore used wherever possible (Zaß, 2012).

Not only the quality of the thermal storage (stratification efficiency and thermal insulation) has an influence on the efficiency of the solar thermal combi system, but also the IWH used. This has been studied in the past, especially with respect to small systems without circulation, which are often found in single-family houses (Poppi et al., 2016; Poppi and Bales, 2014; Ruesch and Frank, 2011).

Thus, the selection of the IWH has an impact on the cooling of the primary return and therefore the efficiency of the entire system. The size of the heat exchanger determines the minimum storage temperature needed to cover the required maximum load peak, which in turn depends on the tap profile used. Another aspect that affects the efficiency of the combi system is the hydraulic concept and the control strategy used. They should guarantee a constant DHW temperature on the one hand, but on the other hand they also have an influence on the return temperature. When comparing different hydraulic concepts and control strategies, a speed-controlled regulation of the primary pump by means of a microprocessor without a primary mixing valve turned out to be the most effective variant, since a very precise adjustment of the volume flow and an effective cooling of the return flow can be achieved here. But also proportional controller with regulating valve or turbine pump leads to energy savings compared to typical systems provided with internal heat exchanger. (Bales and Persson, 2003)

Differences between idealized heat exchangers (infinite transfer area) and real IWH with large heat exchangers and well-functioning control are minimal (Ruesch and Frank, 2011). The size of the heat exchanger has a significant impact on the electricity consumption in a solar thermal heat pump combi system, as it determines the required storage temperature (Poppi et al., 2016).

Maintaining storage stratification is one of the challenges posed by the use of DHW circulation. Thus, increased return temperatures have a negative impact on the efficiency of the system and, depending on the hydraulic and controller concept, can result in over 10 % higher energy consumption (Ruesch and Frank, 2011). In pure circulation operation, very high primary return temperatures occur, which explains the advantage of a temperature-dependent stratification of the primary return into the buffer storage, especially in the case of high DHW set point temperatures and the associated high temperatures in the circulation return (Peuser et al., 2009; Zaß, 2012). Since circulation is mandatory, especially for large potable water installations, such as in multi-family houses (DIN, 2012), the following section examines which technical characteristics of an IWH enable the most efficient solar thermal combi system for a large DHW installation.

3. Simulation boundary conditions

The investigations in this study are carried out in TRNSYS (version 17.02.0005) for a multi-family building with 8 apartments as described by Mercker and Arnold (2017). The DHW is provided by a central IWH, and a circulation system ensures comfort and hygiene. The central heating system consists, as shown in Fig. 2, of a solar thermal system and a gas boiler, which heat a buffer storage in bivalent mode. The reference system consists of a smaller buffer storage heated by a gas boiler.



Fig. 2: Schematic of the investigated DHW-system of a multi-family house (reference system on the left side)

The tapping profile with a resolution of 1 min was generated for the building with 8 apartments using DHWcalc version 2.02b (Jordan et al., 2019). For 12 to 16 persons, a daily draw-off volume of 440 l at 60/10 °C is assumed, and summer vacations are also taken into account. An IWH is used, which can provide the required peak power of approx. 120 kW (\triangleq 34 l/min at 60/10 °C).

The minimum tapping time, which can be set in DHWcalc, is 1 min. The simulation time step is set to 2 s. However, 1 min is longer than the most tapping processes during hand washing, which is why we assume that the number of these events is underestimated. However, the heat demand occurs mainly during showering and bathing. For our results, we therefore expect to slightly underestimate the importance of return diversion.

The condensing gas boiler is controlled by a thermostatic control. The temperature sensor used for this purpose is located centrally between the supply and return pipes in the storage. There is a fixed difference of 5 K between the switch-on and switch-off temperature. The specific temperature values are part of a minimizing algorithm, which takes into account DHW penalties (see below).

The modulating condensing gas boiler is simulated with Type 204, which was developed at ISFH (Glembin et al., 2013). The boiler has a water content of 7.3 l and a heat output of 28 kW at 60 °C inlet temperature, which can be controlled with a minimum degree of modulation of 28 %.

Type 832 is used for the simulation of the solar thermal collector. The collector area is assumed to be 4 m^2 per apartment, which results in a total area of 32 m². This corresponds to the recommendations of Mercker and Arnold (

2017). The heat is transferred to the storage via an external heat exchanger with a UA-value of 120 W/K per m² of collector area (VDI, 2014). The temperature sensor for the control of the solar circuit is located in the middle between the flow and return of the lower solar circuit. In general, the solar flow can load the upper or lower part of the storage. This loading is temperature dependent. For the upper part to be loaded, the secondary outlet temperature at the heat exchanger must exceed the storage temperature of the upper solar circuit (measured in the middle between the flow and return of the corresponding circuit). The primary pump is started when the collector temperature exceeds the storage temperature by 15 K and is stopped when the difference is less than 5 K. The controller starts the secondary pump when the temperature in the primary side heat exchanger flow exceeds the storage temperature by 7 K and both pumps are stopped when this difference falls below 3 K. The pumps are operated in low-flow regime at 20 l/(m² h). At a storage temperature of 95 °C, the secondary pump is switched off and the primary pump runs until a collector temperature of 130 °C is reached. There is no communication between the heat generators, i.e. they are operated in bivalent-parallel mode.

For the simulation of the buffer storage Type 340 (Drück, 2006) is used. Two variants are simulated here: the first variant for the solar combi system has a volume of 1,600 l and a height of 1.8 m. For the reference system, the storage size was set to 640 l with a height of 0.72 m. The connection heights for both variants can be taken from Tab. 1 relative to the overall height of the storage. The heat losses of the storage are approx. 10 kWh/d.

Solar combi system	Reference system
1.8 m	0.72 m
1,6001	640 1
0.8	0.5
0.6	0.01
0.65	-
0.45	-
0.45	-
0.05	-
1	1
0.01	0.01
0.5	0.1
	Solar combi system 1.8 m 1,600 l 0.8 0.6 0.65 0.45 0.45 0.05 1 0.01 0.5

Tab. 1: Parameters and relative connection heights of the storage . .

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As reference we assume thermostatic mixing valves for the taps in the apartments with a set temperature of 45 °C, since this temperature corresponds to the DHWcalc profiles. The volume flow is recalculated based on the DHWcalc file and a fluctuating cold water temperature as described by IEA TASK 32 (Heimrath and Haller, 2007). The flow rate through the IWH V_{IWH} is given by

$$\dot{V}_{IWH} = \dot{V}_{tap} \cdot \frac{\vartheta_{tap,45^{\circ}C} - \vartheta_{PWC}}{\vartheta_{pipe,out} - \vartheta_{PWC}}$$
(eq. 1)

where $g_{pipe,out}$ corresponds to the variable hot water temperature before the mixing valve.

To find the lowest possible set temperature for the gas boiler, penalties are introduced. The simulation is aborted and not investigated further when the hot water temperature *B*_{pipe,out} drops below 44 °C or the temperature at the outlet of the IWH drops below 60 °C. '

For circulation, 3 variants are considered. The basic variant assumes an existing building with 48 m uninsulated pipes. This corresponds to a 4-floor building with 3 m of pipe duct length in each floor for flow and return. In this case, the circulation volume flow is 160 l/h, whereby the return temperature does not fall below 55 °C in steady-state operation. This corresponds to losses of approx. 1070 W. In order to investigate the influence of the circulation, 2 further simplified variants were investigated: one with losses of approx. 200 W (representing insulated pipes) and one with losses of approx. 5350 W (representing longer pipes and more junctions). For simplification purpose, the pipe length and the volume flow were multiplied by the factor 0.2 and 5, respectively. This results in circulation volume flows of 32 l/h and 800 l/h. During a tapping event, the circulation volume flow is set to 0 l/h for simplicity.

4. Investigated parameters

Many technical properties of IWH are not accessible to the specialist planner and installer. This makes it difficult for them to choose the correct product for regenerative heat supply systems, especially with regard to efficiency and sustainability, but also with regard to economic efficiency.

In order to address this problem, four module types of electrical IWHs are considered, which were identified during a market investigation. The hydraulic circuits of these module types are schematically shown in Tab. 2.





Basically, the IWH differ in the specific heat transfer rate, which is abbreviated as *UA* (note that it indicates here a property of the IWH and not only of the heat exchanger) and the actuating time between circulation and tapping mode. In Fig. 3 the three most important quality characteristics for the thermal energy efficiency are shown, which are influenced by these properties. Here, a module based on Concept II is used, which is used in TRNSYS to model all module types.



Fig. 3: Generic instantaneous water heater model for simulating large DHW-systems with three quality measures

To keep the thermal losses as low as possible and the solar fraction (or heat pump fraction) as high as possible, a low required set temperature (point 1) is required. This set temperature is determined by the temperature difference required by the module between the heating water inlet and the DHW outlet. The temperature difference depends not only on the heat exchanger but on the entire module hydraulics.

Another crucial point is the return temperature of the primary side (point 2). If this is lower, it increases the efficiency of all heat generators and leads to lower volume flows on the primary side and thus to less mixing in the storage.

In order to maintain the stratification of the storage, the return of the primary side is connected to the center of the storage in pure circulation mode. The circulation inlet has a temperature of at least 55 °C at the central IWH, so that this temperature is not undercut on the primary side. If tapping occurs, the return temperature drops sharply due to the dominant cold water temperature and the three-way reversing valve must switch to the lower storage connection with the shortest possible actuating time in order to maintain the storage stratification (point 3).

To determine the specific heat transfer rates (UA-values), we carried out laboratory measurements with several IWHs. We found that the UA-values can be approximated with the following equations.

$$UA = f_{\vartheta} \cdot \left(-3 \frac{W/K}{(l/min)^2} \cdot \dot{V}_{sec}^2 + 295 \frac{W/K}{l/min} \cdot \dot{V}_{sec} \right) \cdot f \qquad (eq. 2)$$

with $f_{\vartheta} = \left(1.0395 - 0.008 \cdot \left(\vartheta_{P,in} - 60^{\circ}C \right) \right) \qquad (eq. 3)$

The definition of the temperature correction factor f_{ϑ} (see eq. 3) is limited to primary inlet temperatures $\vartheta_{P,in}$ between 60 and 90 °C. The specific heat transfer coefficient (UA) is obtained in W/K where the secondary side flow rate \dot{V}_{eec} is in l/min. The performance of different IWH modules can be adjusted by the factor f, which was varied between 1.0 and 2.5 in these simulations.

The results of the UA-value calculation according to eq. 2 compared to six real measured stations are shown in Fig. 4 for primary inlet temperatures of 70 °C and 90 °C. The cold water temperature is 10°C and the domestic hot water temperature is 60°C. A standard system for small systems according to Concept 1 is mapped using a factor f = 1.0to 1.5. The performance is sufficient for the multi-family house tapping profile shown, if the temperature in the buffer is high enough. Stations according to this concept are the products Ia, Ib and Ic. Larger modules for multi-family houses according to concept II and III are represented by f = 1.5 to 2.0. Particularly efficient heat exchangers or concept IV with 2 heat exchangers connected in series are represented by a factor f = 2.5. In general, the measured IWHs are only a random sampling. Each IWH module concept can achieve the same characteristics, but at different costs, which is why this study does not consider station concepts but only characteristics.



Fig. 4: Comparison of different measured UA -values (points) of six different IWH at 70 °C/60 °C/10 °C (left) or 90/60/10 °C (right) with calculation results according to eq.2 for different factors f (lines)

In circulation mode, a constant *UA* value is assumed. This depends on the volume flow rate and accounts to, 500 W/K at 0.2 kW and 1 kW circulation loss and to 2000 W/K at 5 kW circulation loss.

Type 84 (moving average) is used to model the actuating time (t_{RL}) of the primary return between the lower and middle storage areas. It is between 2 s and 130 s. Tab. 3 shows all values and an overview of all varied parameters. The upper set point temperature of the storage used for the control of the gas boiler is determined via minimization.

For the reference system the IWH concept I with a UA-value f = 1.0 is used, the return flow is always at the bottom inlet.

Factor <i>f</i> for UA	Actuating time <i>t</i> _{RL}	Circulation heat loss rate	Set temperature of upper storage
1.0	2 s	1.07 kW	Find minimum ()
1.5	18 s	0.20 kW	
2.0	34 s	5.35 kW	
2.5	50 s		
	66 s		
	82 s		
	98 s		
	114 s		
	130 s		
	Always bottom		

Tab. 3: Overview of the varied parameters in the simulation

5. Results

When evaluating the simulations, the mean upper storage temperature, which is typically higher than the set point, is considered first (Fig. 5). Here, a clear dependence on the *UA*-value is noticeable: as expected, the required storage temperature decreases with increasing *UA*-value. For the return diversion (effects represented by the error bar) and the circulation losses, on the contrary, no clear tendency can be observed. This can be probably explained by slight changes in the recharging behavior of the heat generators and thereof resulting penalties. Real DHW installations will be more tolerant with regard to short-time temperature drops of the outlet temperature than our penalty conditions, so that lower storage temperatures would be possible.



Fig. 5: Mean upper storage temperature depending on circulation loss an UA-value for the solar combi-system

The main focus of the evaluation, is on the CO₂ savings $f_{sav,CO2}$ (cf. eq. 4) compared to the respective reference system. There is one reference value for each circulation loss.

$$f_{sav,CO2} = 1 - \frac{(Q_{Gas} \cdot f_{Gas,CO2})}{(Q_{Gas} \cdot f_{Gas,CO2})_{ref}}$$
(eq. 4)

For this, the gas consumption Q_{Gas} of the respective system is multiplied by the emission factor $f_{\text{Gas,CO2}}=250 \text{ gCO}_2\text{-eq/kWh}_{\text{Gas}}$ for natural gas (Fritsche, 2016). This also takes upstream emissions and other greenhouse gases into account. The electricity consumption of the system, for solar thermal and gas burner is negligible.

A comparison of the bivalent system with the reference system shows that the CO_2 savings clearly depend on the circulation load, as the collector area is constant (see Fig. 6).

A low circulation loss with the same tap profile leads to significantly higher CO₂ savings. Thus, in the case *UA*-value f = 1 and no return diversion the savings increase from 15% at 5 kW to 36% at 1 kW and 51% at 0.2 kW. With higher circulation losses, the total consumption of the system increases and this additional energy is required at a temperature level between 55 and 60 °C, which can be reached much less frequently compared to preheating the cold water at the storage tank inlet.

Both varied parameters of the IWH have an influence on the results. Fast switching of the return diversion has a positive effect on CO_2 savings, as it contributes to the formation of a cold zone in the lower part of the storage. Furthermore, a good heat transfer performance *f* of the IWH leads to lower required storage temperatures (see Fig. 5) which in turn ensures that less energy has to be provided by the gas boiler.

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In general, all concepts manage to supply the multi-family house with hot water without penalty. With a circulation loss of approx. 1 kW, however, IWH for single-family houses can only achieve a saving of 36 %, and with an improvement of the *UA*-value, up to 5 pp. can be gained. The influence of the return diversion shows a large influence especially for higher *UA*-values, thus the introduction of a slow return diversion with a actuating time of 130 s already leads to an improvement up to 4 pp. and a fast return diversion to a further improvement by about 4 pp. The influence of the *UA*-value also increases to 9 pp.

A similar behavior can be observed for the other two investigated circulation losses, where the scatter caused both by the *UA*-value change and by the return diversion decreases for large circulation volume flows and increases for small ones, which can also be explained by the reasons already described.



Fig. 6: Annual CO₂ savings of the system depending on UA-values, actuating times and circulation losses

Furthermore, we calculated the solar fraction f_{sol} according to eq. 5. This value gives information whether a good storage stratification occurs and a cold preheating zone is created. For this purpose, the solar energy Q_{sol} fed into the storage is put into relation with the sum of Q_{sol} and the energy of the gas boiler Q_{Boiler} .

$$f_{sol} = \frac{Q_{sol}}{Q_{Boiler} + Q_{sol}} \tag{eq. 5}$$

The solar fraction shows an analogous behavior to the CO_2 savings. The solar utilization ratio η_n is calculated according to eq. 6.

$$\eta_n = \frac{Q_{sol}}{Q_G * A_{koll}} \tag{eq. 6}$$

Here, the proportion of the solar radiation energy Q_G incident on the collector area A_{koll} used by the system is calculated.

Fig.7 shows the solar fraction and the solar utilization ratio over the specific energy demand per collector area. Different technical properties of IWH cause a variation of 12 % in both, solar fraction and solar utilization ratio. Here the daily specific energy demand per m² of collector area is used, which results from the energy demand for tapping and circulation load, whereby in this paper the circulation load is the only variable.



Fig. 7: Solar fraction and utilization ratio of the solar thermal system with different specific heat demands (error bars show the variation due to different IWH properties)

6. Summary

Over the last years, the heating energy demands of residential buildings have been reduced more and more. As a result, the focus has shifted to heating of domestic hot water, as it determines the required temperature level of the heat generation system. For large domestic hot water installations, IWH systems in combination with a bivalent heating system have emerged as a possible solution for decarbonization, as they create a cold preheating zone in the buffer storage which enables the efficient operation of renewable heat generators such as heat pumps and solar thermal systems.

We investigated an exemplary bivalent heating system consisting of solar thermal and gas boiler for a multi-family house. In addition to different circulation losses, 4 concepts of IWHs with different parameters for the heat exchanger capacity and the return diversion were analyzed. The variation of circulation losses between 0.2 to 5 kW changes the solar fraction between 14 to 50 %, which argues for a consistent insulation of all pipes of the circulation circuit and a compact design of the installation. With regard to the results of the low circulation losses, an effective IWH with high *UA*-values and short actuating times of the return diversion can increase the CO_2 savings from 50 % to 65 %. However, the sensitivity of CO_2 savings with regard to these parameters decrease with low solar fraction (high circulation losses).

For the given demand profile and optimization rule, the required storage temperatures (between 72 and 84 °C), which play a major role for solar thermal systems but also for heat pump systems and the reduction of district heating temperatures, are mainly dominated by the *UA*-value. The actuating time of the return diversion has no significant influence on the required storage temperatures.

In general, the simulation results show that a return diversion is advantageous and if it is present, that it should be as fast as possible. This can increase the efficiency of the solar thermal system.

7. Outlook

The results are influenced by the penalty rule that needs further investigation. How long can the outlet water temperature of the water heater be lower than 60 °C without being a design error? This is especially relevant for temperature sensitive heat generators, such as heat pumps, which should be investigated in future work. Furthermore, the influence of other tapping profiles and a variable collector area should be investigated.

8. Acknowledgement

The work is carried out within a joint project of ISFH with Viega GmbH & Co. KG under grant number 03EN1025A (TA-DTE-XL). The authors are grateful for the support of the Federal State of Lower Saxony and the Federal Ministry for Economic Affairs and Climate Action (BMWK). The authors are responsible for the content and would also like to thank PAW GmbH & Co. KG, Oventrop GmbH & Co. KG, Solvis GmbH, Malotech GmbH, cbb software GmbH, Taconova GmbH, Reich + Höscher, Varmeco GmbH & Co.KG, Bosch Solarthermie GmbH and Vaillant GmbH for their support.

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Experimental investigation on direct expansion solar assisted heat pump system employing a novel PVT module

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Abstract

The system performance of the solar assisted PVT (photovoltaic-thermal) heat pump (SA-PVT-HP) system was experimentally investigated on a typical winter day in Shanghai. A novel PVT module with optimized fluid channel pattern and manufacture approach was employed as a solar collector/evaporator, and it showed great ability in temperature control of solar cells compared with a single PV module. The results indicated that the COP (Coefficient of Performance) of the SA-PVT-HP system could reach its maximum value of 11.2 which is 180% higher than that of the conventional air source heat pump system, while its average value was 7.1 during the operation under the solar radiation intensity of 585.3 W/m², ambient temperature of 28.0 °C. To be noted, the referenced COP of the air-source heat pump system is 4.0 on an annual average in Shanghai. Moreover, the solar cells' working temperature of the PVT module could be reduced from 36.0 °C to 23.5 °C, and the electrical efficiency could be improved from 17.24% to 18.16% compared with a single PV module.

Keywords: PVT; solar assisted, heat pump, temperature control, comparative study

1. Introduction

The temperature effect of the solar cells is unavoidable during the operation and it would deteriorate its electrical efficiency and service life. The PVT technology is proposed by Wolf et al. (Wolf, 1976) to reduce the working temperature of the PV module, and increase its electrical efficiency. The thermal absorber attached backside of the PV module could extract the waste heat of solar cells through different working fluids like air, water, refrigerant, etc. Among these, the refrigerant-based PVT module has better performance in heat absorption capacity due to the evaporation process. Moreover, the grade of the thermal energy could be improved effectively through the heat pump cycle, and then the useful heat could be used for the domestic hot water supply of residential heating.

The sheet-and-tube type PVT module is one type of refrigerant-based PVT module and it is easy to manufacture. Thus, it is used wildly in earlier studies of solar assisted PVT heat pump systems. For instance, Ji et al. (Ji et al., 2009) conducted experiments to evaluate the performance of the sheet-and-tube PVT collector/evaporator. They found that a 1.01 m*0.73 m PVT evaporator could reach 12% of electrical efficiency and 50% of thermal efficiency. Tsai (Tsai, 2015) presents a model of the sheet-and-tube PVT assisted heat pump water heater, and the proposed model could well simulate the system operation status under real-time conditions.

However, the roll-bond type PVT module is more efficient in the heat transfer process due to the larger heat exchange area. Therefore, the roll-bond type PVT module is applied in the heat pump system recently and it has a great improvement in system performance. Del Col et al. (Del Col et al., 2013) comparatively studied the performance of sheet-and-tube type PVT modules and roll-bond type PVT modules, the results indicated that the roll-bond type PVT module performs better in the heat pump system. Zhou et al. (Zhou et al., 2019) tested the roll-bond type PVT module in the solar assisted heat pump system and the electrical efficiency of the PVT module was 11.8% while the system COP was 6.16.

Nevertheless, temperature uniformity is another important issue that should be considered in the structure design of the PVT module because it would cause heat spots and shorten its life. Therefore, a novel roll-bond type PVT module is employed to form a solar assisted heat pump system to realize temperature control of solar cells in this paper. In addition, the PV system is also established as a control group to compare the situation of the solar cells with the PVT module. The objective of this paper is to evaluate the thermal and electrical performance of the novel PVT module experimentally as well as the performance of the solar assisted PVT heat pump system.

2. System description

The schematic diagrams of the solar assisted PVT heat pump (SA-PVT-HP) system and PV system have shown in Fig. 1. The PVT module employed in the SA-PVT-HP system is a combination of a roll-bond collector/evaporator and a conventional PV module, and these two components are attached through EVA grease. The SA-PVT-HP system consists of the PVT modules, gas-liquid separator, compressor, water tank (condenser), expansion valve, MPPT controller, accumulator, and DC load. The PV system consists of the PV modules, MPPT controller, accumulator, and DC load. The FV systems were conducted under the same conditions to reveal the temperature control ability of the PVT module compared with a single PV module. Moreover, the heat pump performance of the SA-PVT-HP system was also investigated in this study.

The solar power units of these two systems were composed of the MPPT controller, the accumulator, and the DC load. Moreover, the specific parameters of the solar cells were the same as the PVT module and the PV module. In the SA-PVT-HP system, the PVT module was adopted as the evaporator which uses the refrigerant as a working fluid to absorb heat from the solar cells. The PVT collector/evaporator, compressor, condenser (which is encapsulated in the water tank), and expansion valve formed the thermodynamic cycle of the PVT heat pump system. To be noted, the PV system was set as a control group in comparison to the electrical performance of the PVT module and the PV module.

In the PV system, the solar energy was converted to electricity through the photovoltaic effect and the electrical energy was controlled by the MPPT controller. Meanwhile, a portion of the solar radiation which could not excite electron transitions would be absorbed by the solar cells and then rise its operating temperature. Subsequently, the high operating temperature has adversely impacted the PV module due to the temperature effect and caused a reduction in the electrical efficiency of the solar cells ultimately.

In contrast, the PVT module in the solar assisted PVT heat pump system would reduce the operating temperature of the solar cells prominently through the evaporating process. The low-quality refrigerant would extract heat from the solar cells and gradually vaporize to the high-quality refrigerant in the PVT collector/evaporator. The refrigerant vapor would be compressed to a high-temperature and high-pressure state through the compressor and then condensed in the water tank. The thermal energy released by the refrigerant would heat the water in the tank for domestic hot water usage or residential heating. Thus, the solar assisted PVT heat pump system could realize co-generation during the operation.



Fig. 1: The schematic diagrams of the solar assisted PVT heat pump system and PV system

3. Experimental setup

Fig. 2 presents the front view of the solar assisted PVT heat pump system and the PV system. The tilt angle of the modules is 30 degrees (considered the latitude of Shanghai). In the SA-PVT-HP system, two PVT modules are used as an evaporator that could absorb heat from the solar cells. Furthermore, the working fluid in the evaporator could reduce the working temperature of the PV module and then increase its electrical efficiency. The PV system is arranged as a control group to compare the PV module's electrical efficiency in two systems.



Fig. 2: Front view of the experimental rigs

The back view of the experimental rigs as shown in Fig. 3 presents the components' arrangement position in the workbench. For the PV system, the PV modules generate electricity and are controlled by the MPPT controller which is connected to an accumulator. The DC load is applied to consume the electricity powered by the PV modules. For solar assisted PVT heat pump system, it could be divided into two sub-units: the solar power unit and the heat pump unit. The solar power unit has the same system components as the PV system. In the heat pump cycle, the working fluid absorbs heat from the solar cells through the evaporation process and it would be turned into vapor with high enthalpy. Subsequently, the outlet vapor would be

compressed to a high-temperature and high-pressure state through the compressor, and then it would be condensed in the water tank. The condensation heat released by the refrigerant vapor would heat the water to meet the requirement of the domestic hot water supply. The working fluid would flow into the PVT collector/evaporator for another thermodynamic cycle after expansion through the expansion valve.



Fig. 3: Back view of the experimental rigs

As shown in Table. 1, the specific characteristics of each component are listed. The areas of the PVT module and PV module are 1.14 m^2 and 1.01 m^2 , respectively. A 150L water tank is used as a condenser to heat the water. Both the PVT module and PV module are arranged with 30 degrees angle facing south for higher solar irradiation.

Parameters	Nomenclature	Value	Unit
Volume of the water tank	Vwater	150	L
Rated power of the compressor	P _{com}	565	W
Length of the PVT module	LPVT	1680	mm
Width of the PVT module	W _{PVT}	1000	mm
Area of the PVT module	Apvt	1.68	m ²
Length of the PV module	L_{PV}	1680	mm
Width of the PV module	W_{PV}	1000	mm
Area of the PV module	A_{PV}	1.68	m ²
Standard solar cells' electrical efficiency	η_e	19.94	%
Temperature coefficient of the solar cell's electrical efficiency	β_e	-0.39	%/°C
Tilt angle	θ	30	degree
Refrigerant type	ref	R134a	[-]

Tab. 1: System configurations of the SA-PVT-HP system and PV system

Fig. 4 shows the photograph of the novel PVT module. The rear side of the PVT module shows the fluid channel pattern of the roll-bond panel. This structure considers the thermal performance, temperature uniformity, and hydraulic performance simultaneously. The fluid channel pattern consists of hexagon, grid, and linear type fluid channel units. The fluid channel patent design is based on the authors' previous work (Yao et al., 2020; Yao et al., 2022; Yao et al., 2021), and for this novel structure proposed in this paper, the arrangement of the grid and linear type units ensure the flow of working fluid in the corners of the PVT module, in this regard, the corner temperature uniformity could be improved. Furthermore, the junction box of this type of PVT module is smaller and therefore the hole in the roll-bond panel could be smaller to

improve the heat exchanging performance. The rear side of the PVT module is painted black to absorb heat from the reflective solar irradiation of the ground. In this way, the thermal efficiency of the PVT module could be further improved.



(a)

Fig. 4: Photograph of the novel PVT module

4. Results and discussion

The field tests of the solar assisted PVT heat pump system and the PV system were conducted on a typical cloudy day in Shanghai. The PVT module's thermal and electrical performance, as well as the solar assisted heat pump system's performance, were experimentally investigated compared with a single PV module. Additionally, the temperature distributions of the PVT module and PV module were compared through the infrared camera to further indicate the temperature situation of the solar cells in these two systems.

Table.1 presents the boundary conditions of the field test of the SA-PVT-HP system and PV system. The average ambient temperature is 28 °C while the average solar radiation intensity is 585.3 W/m², and the initial water tank temperature is 33.7 °C.

Parameters	Value	Unit
Date	2021.05.31	[-]
Operating period	10:10~11:35	[-]
Average ambient temperature	28	°C
Average solar radiation intensity	585.3	W/m ²
Wind speed	0~3	m ²
Refrigerant charge	800	g
Tilt angle	30	degree
Initial water tank temperature	33.7	°C

Tab. 2: Boundary conditions of the field test

The experimental results of the SA-PVT-HP system have shown in Table. 3. The average COP of the system could reach 7.1 which is 77.5% higher than the conventional air-source heat pump system. To be noted, the referenced COP of the air-source heat pump system is 4.0 on an annual average in Shanghai (China, 2008). The peak value of the COP is 11.2 which shows the remarkable performance of the heat pump system. The final water tank temperature is 60.4 °C which could meet the heat demand of the domestic hot water usage or residential heating. During the 1.4 hours of operating time, the total energy consumption of the compressor is
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0.7 kWh while the average compressor power is 490.8 W, this value is lower than the rated power of the compressor which means the compressor performance could be further improved through the better arrangement of the system configuration. From the aspect of the PVT module, the inlet temperature is around 22.0 °C and the superheat degree is 8.5 °C. The PVT module has a mild pressure loss due to the optimized fluid channel pattern, and its dimensionless pressure loss is only 0.078. The condensing pressure is 1.438 MPa while the inlet pressure of the compressor is 0.496 MPa, thus, the compression ratio of the compressor could be calculated as 2.9.

Parameters	Value	Unit
Average COP	7.1	[-]
Maximum COP	11.2	[-]
Initial water tank temperature	33.7	°C
Final water tank temperature	60.4	°C
Running time	1.4	hours
Total energy consumption of the compressor	0.7	kWh
Average compressor power	490.8	W
Inlet temperature of the PVT module	22.0	°C
Outlet temperature of the PVT module	30.5	°C
Temperature difference between inlet and outlet of the PVT module	8.5	°C
Inlet pressure of the PVT module	0.562	MPa
Outlet pressure of the PVT module	0.520	MPa
Pressure loss of the PVT module	0.042	MPa
Dimensionless pressure loss of the PVT module	0.078	[-]
Inlet pressure of the compressor	0.496	MPa
Condensing pressure	1.438	MPa
Compression ratio	2.9	[-]

Tab. 3: Experimental results of the SA-PVT-HP system

Table. 4 shows the comparison results of the electrical performance of the PVT module and the PV module. The operating temperature of the solar cells could reduce from 36.0 °C to 23.5 °C of the PVT module due to the evaporating process of the cooling panel. In this regard, the electrical efficiency of the solar cells could be improved from 17.24% to 18.16% due to the low working temperature.

Tab. 4: Comparison of results of the electrical performance of the PVT and PV modules

Parameters	PVT module	PV module
Output current	6.65 A	6.22 A
Output voltage	68.6 V	69.6 V
Output power of one piece	228.1 W	216.5 W
Electrical efficiency	18.16%	17.24%
Efficiency improvement	5.38%	[-]
Operating temperature	23.5 °C	36.0 °С
Temperature reduction	12.5 °C	[-]

The temperature uniformity is another indicator to evaluate the performance of the module. Fig. 5 presents the infrared images of the PVT module and PV module during the operation. It could be found that the temperature difference of the PVT module could be controlled within 2.4 °C while the temperature difference of the PVT module is around 4.2 °C. In this regard, the temperature uniformity of the PVT module

is better than the PV module. The temperature difference of the existing PVT module (Buonomano et al., 2016) is around 5 °C and the temperature of the PV cells is between 29.4~34.4 °C, thus, compared to the existing PVT module, The proposed PVT modules have better temperature uniformity and lower working temperature of the PV cells. Moreover, the low operating temperature of the PVT module would also benefit the electrical performance and service life of the solar cells.



Fig. 5: Infrared images of the PVT module and PV module during operation

5. Conclusions

In this paper, a novel PVT module was manufactured and employed in the solar assisted PVT heat pump system, and then evaluated its performance compared with a single PV module. The results revealed that the PVT module shows the remarkable temperature control ability of solar cells and improves its electrical efficiency significantly. Furthermore, the solar assisted PVT heat pump system was found high-efficiency compared with conventional air source heat pump system which shows great potential in building solar energy utilization. The long-term operation test would be done in a future study to ensure the system's stability.

6. Acknowledgments

This publication has been jointly written within the cooperative project "Key technologies and demonstration of combined cooling, heating and power generation for low-carbon neighbourhoods/buildings with clean energy – ChiNoZEN". The authors gratefully acknowledge the funding support from the Ministry of Science and Technology of China (MOST project number 2019YFE0104900), and from the Research Council of Norway (NRC project number 304191 - ENERGIX)

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H-04. Technical Characterization: Testing, Standards and Certification

A detailed dynamic parameter identification procedure for quasidynamic testing of solar thermal collectors

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Abstract

There are two procedures for parameter identification in the standard quasi-dynamic testing of solar thermal collectors: multilinear regression (MLR) and dynamic parameter identification (DPI). The main advantage of DPI is that it is more flexible with respect to the collector model, allowing the use of more sophisticated thermal models and the reduction of testing time. However, most of the implementations available in the literature require non-free close source software, making its replication a difficult task for most testing laboratories. In this work we show a specific implementation of a dynamic parameter identification procedure for a flat plate collector. The algorithm is described in detail, and we also provided a free open-source code in Matlab, facilitating the reproduction of our work and attempting to extend the use of this procedure. We validated its implementations against the standard MLR, comparing the model parameter's values, the efficiency curve and the useful power produced by the collector under the Reporting Standard Conditions defined by the ISO 9806 standard. The measurements were taken in local test facility that compliant with the ISO 9806:2017 requirements.

Keywords: Solar thermal collectors, parameter identification, quasi-dynamic testing, ISO 9806.

1. Introduction

The ISO 9806 (2017) is the most used standard to characterize the thermal performance of solar collectors. It establishes a general thermal model that can be used for a wide variety of technologies: uncovered collectors, flat plate, vacuum tubes, concentrating collectors, etc. This standard admits two test methodologies: Steady State Testing (SST) and Quasi-Dynamic Testing (QDT). For the latter, the determination of the models' parameters (parameter identification) can be done in two different ways. The first one consists in approximating the time derivative by using finite differences and treating it like an independent variable for a multi-linear regression (MLR), which is the most used tool. The second one consists in performing a dynamic simulation coupled with a nonlinear regression algorithm (Dynamic Parameter Identification, DPI). Fischer et al. (2003) showed the equivalence between these two procedures for four different flat plate collectors.

The MLR procedure requires the model to be linear with respect to its parameters, which imposes important limitations on the collector modeling. The DPI procedure is more flexible than MLR with respect to the form that the collector's model can take, allowing the use of more sophisticated thermal models. For instance, it allows the use multi-nodes models, which have been proven to be suitable for in-situ testing, as they are capable of handling large variations in the fluid temperature at the inlet of the collector (Muschaweck & Spirkl, 1993; Fhar et al., 2018). DPI also admits the use of low temporal resolution test data, 10-seconds for example, as shown in Hoffer et al. (2015). The combination of multi-nodes models and low temporal resolution test data allows to better reproduce the real dynamics of the collector, improving the modeling of the transient phenomena and resulting in shorter testing times (Hoffer et al., 2015). Finally, DPI makes it easier to incorporate non-linear incident angle modifier, like the Ambrosetti function for flat plate collectors (Bosanac et al., 1994; J.M. Rodríguez-Muñoz et al., 2021a) or the biaxial incident angle modifiers of tubular collectors. However, the DPI procedure has the disadvantage that its implementation requires the use of more complex mathematical tools. Some implementations of this procedure are described in the literature, but they are based on the use of closed code or paid programs, which makes their replication difficult (Muschaweck & Spirkl,

1993; Hoffer et al., 2015).

In this work we describe in detail a specific implementation of a DPI procedure for a flat plate collector. The algorithm is implemented for this type of collector, and it is validated against the standard MLR procedure, comparing the model parameter's values, the efficiency curve and the useful power produced by the collector under the Reporting Standard Conditions defined by the ISO 9806 standard. A free and explained code in Matlab is also provided, facilitating the reproduction of our work and attempting to extend the use of this procedure int other testing laboratories. The availability of such free and open algorithms represents an important basis for future research in the field of solar collector testing. It will allow the evaluation of different solar collector models with the aim of improving the description of the transient behavior sin solar collectors and the reduction of testing times, which is part of our current work.

This article is organized in the following way. Section 2 describes both parameter identification procedures MLR and DPI. Section 3 describes the test facility and the test data used for this work and Section 4 presents the results. Finally, Section 5 summarizes our conclusions.

2. Description of parameter identification procedures

2.1 Thermal model

The ISO 9806:2017 standard proposes a general thermal model that can be applied to different kinds of solar thermal collectors' technologies. Depending on the collector type, some terms and coefficients can be neglected in the general model. Eq. 1 shows the thermal model for low temperature collectors with cover.

$$\frac{Q_u}{A_G} = \eta_{0,b} \cdot [K_b(\theta) \cdot G_b + K_d \cdot G_d] - a_1 (T_m - T_a) - a_2 (T_m - T_a)^2 - a_5 \frac{dT_m}{dt}$$
(eq. 1)

where G_b and G_d are the direct and diffuse solar irradiance on the collector plane, respectively, T_m is the mean temperature of the working fluid (the average between the inlet temperature, T_i , and the outlet temperature, T_o), T_a is the temperature of the surrounding air, and the characteristic parameters are: $\eta_{0,b}$, $K_b(\theta)$, K_d , a_1 , a_2 y a_5 . The first three parameters are related with the optic efficiency, a_1 and a_2 are the heat loss factor parameters (where the a_2 coefficient is needed for modeling the non-linear radiative losses) and a_5 is the effective thermal capacity divided by the gross collector area (A_G). All these parameters are assumed to be constants (since the test is carried out at constant flow rate) except for the incident angle modifier for the direct solar irradiance, $K_b(\theta)$. For this last parameter, the expression of eq. 2 can be used, where θ is the angle of incident (Souka & Safwat, 1966).

$$K_b(\theta) = 1 - b_0 \left(\frac{1}{\cos(\theta)} - 1\right) \tag{eq. 2}$$

2.2 Multilinear regression algorithm

The application of the MLR algorithm requires the definition of the dependent variable, in this case, the useful power produced by the collector per unit of gross area, and the definition of the independent variables, in this case: G_b , $(1/\cos(\theta)-1)$ Gb, G_d , (T_m-T_a) , $(T_m-T_a)^2$ y d T_m /dt. The last variable is approximate by finite difference using the measured data. Then, the characteristic parameters are determined by the following equation, which is a standard multivariate least mean squares algorithm:

$$p = (X^T X) X^T y \tag{eq. 3}$$

In this equation p is a vector containing the parameters' values, X is a matrix with the independent variables as columns and y the dependent variable. The uncertainty for each parameter is derived from the covariance matrix, whose detailed calculation can be consulted in Kratzenberg et al. (2006).

2.3 Dynamic parameter identification algorithm

The DPI procedure implemented in this work is summarized in Fig. 1. This is an iterative procedure that begins with an initial guess of the parameters' vector p (a seed), and uses the measured data, the thermal model given by eq. (1) and a cost function to determine an optimal value of p within a certain tolerance. Each part of this algorithm is described separately below.

The first step is the definition of a cost function. In the field of solar collector testing, a proper cost function is

the mean square error of the useful power estimation,

$$E_c(p) = \frac{1}{M} \sum_{i=1}^{M} \left[\dot{Q}_u - \dot{Q}_u^*(p) \right]$$
(eq. 4)

where M is the number of measurement and the superscript * indicates that the variable corresponds to a theoretical model's estimate. This nomenclature is introduced with the aim of facilitating the differentiate between model's estimate (\dot{q}_u, T_m^*) and the measured data (\dot{q}_u, T_m) . It is noted that the cost function depends on the vector of parameters p.



Fig. 1: Illustration of the dynamic parameter identification procedure.

The second step is the implementation of a numerical method to solve the differential equation given by eq. (1). The output variables (\dot{Q}_u^*, T_m^*) are obtained based on the input variables and a set of characteristic parameters *p*. The input variables correspond to measurements of relevant variables in collector modeling, such as T_i(t), T_a(t), m(t), G_b(t) and G_d(t), which are static functions of time in each iteration. The characteristic parameters of the collector vary in each iteration. For convenience, eqs. (1) and (2) are rewritten as follows,

$$F(t, T_m^*) = \frac{1}{a_s} \left[\eta_{0,b} \cdot \left(1 - b_0 \left(\frac{1}{\cos(\theta)} - 1 \right) \right) \cdot G_b + \eta_{0,b} \cdot K_d \cdot G_d - a_1 (T_m^* - T_a) - a_2 (T_m^* - T_a)^2 - \frac{2\dot{m}c_p (T_m^* - T_l)}{A_G} \right] \text{ (eq. 5)}$$

Assuming that the value of T_m^* at the initial time, t_0 , is known, the value of T_m^* at a generic time t_i , that is, $T_m(t_i)$, is determined by integrating eq. (5) between the instants t_i and t_{i-1} . This integral is performed using the trapezoid methods, i.e., the area under the curve is approximated by the area of a trapezoid as follows:

$$T_m^*(t_i) = T_m^*(t_{i-1}) + \frac{\Delta t}{2} \left[F(t_i, T_m^*(t_i)) + F(t_{i-1}, T_m^*(t_{i-1})) \right]$$
(eq. 6)

This equation is not linear with respect to T_m^* , and can be solved, for each instant, by means of a fixed-point iteration. As an initial value to begin this iteration, the solution is joined with the forward Euler method.

$$T_m^*(t_i) = T_m^*(t_{i-1}) + \Delta t F(t_i, T_m^*(t_i))$$
(eq. 7)

The trapezoid method was chosen for its simplicity; however, other integration methods were implemented but no significant differences in results were obtained.

Then, the theoretical estimate of useful power can be calculated as follow,

dT³

$$\dot{Q}_u^* = 2\acute{m}c_p(T_m^* - T_i) \tag{eq. 8}$$

The final step is the implementation of a non-linear regression algorithm. This algorithm will find the optimal vector of parameter \hat{p} minimizing the cost function. Many algorithms are available in the literature. In this work a Gauss-Newton algorithm was used (Quarteroni, 2000), which consist of linearizing the function $\dot{Q}_u^*(p)$ around a working point p_0 , that is,

$$\dot{Q}_{u}^{*}(p) \approx \dot{Q}_{u}^{*}(p_{0}) + J(p_{0})(p - p_{0})$$
 (eq. 9)

were $J(p_0)$ is the Jacobian matrix of the function $\dot{Q}_u^*(p)$ evaluated in the working point p_0 . The entries of this matrix are numerically estimated using central finite difference as follow,

$$J(p_0)_{i,j} = \frac{\dot{q}_u^*(t_i, p_0 + \delta p_j) - \dot{q}_u^*(t_i, p_0 - \delta p_j)}{2\delta p_j}$$
(eq. 10)

For δp_j the value suggested by Bates and Watts (1988) was used, that is, $\delta p_j = \varepsilon p_0$, where ε is the epsilon machine. Then, the solution of the linearized sample can be found in the same way as in the linear case. In this sense, the optimal set of parameters, \hat{p} , that minimizes the cost function around the working point is:

$$\hat{p} = p_0 + (J(p_0)^T J(p_0))^{-1} J(p_0)^T [\dot{Q}_u - \dot{Q}_u^*(p_0)]$$
(eq.11)

This procedure is iterative, it stars with an initial seed p_0 and calculates $\hat{Q}_u^*(p_0)$ y $J(p_0)$; then \hat{p} is determined with eq. (11) and the process restart with $p_0 = \hat{p}$. The process continues until the difference between p_0 and \hat{p} is less than a certain tolerance. One drawback of this method is that the solution can converge to a local minimum and not to the global minimum, for this reason, the process is repeated using 10 different randomly generated initial seeds. If the algorithm converges to different solutions, then the solution with the smallest mean square error (global minimum) is chosen. The estimation of the uncertainty of the parameters in this case can be done in the same way as in the linear case, replacing the matrix X by the matrix $J(\hat{p})$. A script in Matlab that allows to calculate the model's parameters and its uncertainty is provided in http://les.edu.uy/RDpub/RBA_DPI_tool.zip

3. Tests facilities and data

3.1 Test facilities

The measurements were taken at the Solar Heaters Test Platform (BECS) of the Solar Energy Laboratory (LES, <u>http://les.edu.uy/</u>) of the Universidad de la República (UdelaR), which is located near the city of Salto (Latitude=31.28°S, Longitude=57.92°W), Uruguay. Recently, the BECS participated in a Latin American inter-comparison of test laboratories organized by the PTB (Physikalisch-Technische Bundesanstalt), the German Metrological Institute, an activity in which the platform obtained the best qualification for almost all tests and just one minor observation in the determination of a secondary variable (Fischer, 2020).



Fig. 2. Test bench.

Fig. 2 show a photo of the test bench. To measure the temperature at the input and output of the collector a 3 wire PT100 with 4-20 mA transmitters from Herten company were used. These sensors were calibrated at LES using a calibrated thermal bath and calibrated reference thermometers, reporting a standard uncertainty (P67, k = 1) of 0.02 °C. Ambient temperature was recorded with a Honeywell 2-wire PT1000 sensor also calibrated at LES with a standard uncertainty of 0.02 °C. The flow measurement was performed with an Endress & Hauser electromagnetic flowmeter with a standard uncertainty of 0.5 % of the measurement. The wind speed parallel to the collector plane was measured with an NGR cup anemometer with a standard uncertainty of 0.25 m/s. The global irradiance in the collector plane was measured with a Kipp & Zonen CMP10 pyranometer. The global irradiance in the horizontal plane (G_h) was measured with a Kipp & Zonen CMP11 pyranometer and the diffuse irradiance in the horizontal plane (G_{dh}) with a Kipp & Zonen CMP6 pyranometer mounted with a shadow band from the same manufacturer. All the pyranometers used are spectrally flat (ISO-9060, 2018), being Class A for the global irradiance measurements and Class B for the diffuse irradiance measurement. The diffuse irradiance measurement (with shadow band) was corrected with the expression provided by the manufacturer (Drummond, 1956). These pyranometers are calibrated annually at the LES according to the ISO-9847 (1992) standard against a Kipp & Zonen CMP22 secondary standard that is kept traceable to the world radiometric reference at the World Radiation Center in Davos, Switzerland. All measurements were recorded every 10 seconds using a Fischer Scientific DT85 datalogger. The direct irradiance in the collector plane G_b was estimated from the G_h and G_{dh} with the following procedure. First, the direct normal irradiance (DNI) was calculated using the closure relation $G_h = DNI \cos \theta_z + G_{dh}$, where $\cos \theta_z$ is the cosine of the solar zenith angle. Then, the G_b was calculated from the DNI, by multiplying with the cosine of the incident angle. A flat plate solar thermal collector with a gross area of 2.02 m^2 was used for this work, which was the reference collector also used in the aforementioned inter-comparison of test laboratories. The hydraulic installation of the BECS is described in detail in Rodríguez-Muñoz et al. (2021a).

3.2 Data

The tests were performed according to the ISO-9806 (2017) standard. During the tests, a wind speed of 3 m/s (spatial average) was imposed along the collector plane by using the air forcers shown in Fig. 2. The fluid flow was set at 2.4 l/min and the tracker inclination angle was set at 45°. The azimuth was adjusted manually or automatically depending on the day type. The day types correspond to specific test sequences defined by the ISO-9806 (2017) standard and there are 4 different day types in total. Each of these sequences (day type) must have a duration of at least 3 hours and may be made up of several non-consecutive subsequences of at least 30 minutes each. The procedure and the purpose of each day type is described in the standard.

Fig. 3 shows the graphs suggested by the standard to assess the variability of the operating conditions of the measurement set, where each data (blue point) corresponds to an average of 5 minutes. In Fig. 3a, clear sky and cloudy conditions can be distinguished, the values that follow a regularity are those associated with clear skies. The red line with slope 1 ($G = G_d$) in this figure is used to perform a basic quality control; the G_d and G_t measurements must be below the red line because $G_d < G$. Fig. 3b shows the different inlet temperatures, and Fig. 3c shows the variability in the incidence angle. In this last graph, the negative and positive values correspond to measurements made before and after solar noon, respectively.

A total of 6780 measurement samples were registered, at a 10 seconds time rate. The data must be averaged every certain period prior to the parameter's identification, a time that is not specified in the standard. Different averaging times were tried between 30 seconds and 10 minutes for the MRL method. We found that the parameters' value does not change significantly except for the one associated whit the thermal capacity, a₅, which tends to a constant value and close to the value obtained with the SST method from an averaging time of 5 minutes. Also, the parameters' uncertainty tends to grow with averaging time. For this reason, we chose a 5-minute averaging time for the MLR method, time that coincides with that used in other publications for this same type of collector (Fisher et al., 2003; Fhar et al., 2018). This study was replicated for the DPI method and was found that the time averaging of 30 seconds is the best for this method. The full study of the effect of time averaging on the results can be found in Rodríguez-Muñoz et al. (2021b).



(a) Diffuse solar irradiance vs global solar irradiance.

(b) Temperature difference vs global solar irradiance.



Fig 3. Data set used for the parameter identification.

4. Results

The characteristic parameters were identified with the two described procedures. Tab. 1 shows the obtained values, uncertainties, and t-ratios (quotient between the value of the parameter and its uncertainty). The parameters' values are similar for both procedures. The higher difference is 14 % and corresponds to the a_2 parameter. In the rest the differences are less than 2 %. However, the best way to compare the thermal loss factors is through a global positive loss factor: $a = a_1 + a_2$ (T_m - T_a). If a temperature difference of 50 K is considered, the global loss factor is 4.669 W/m².K for the MLR and 4.667 W/m².K for the DPI, being the difference less than 0.1 %. Complementing this information, Fig. 4 shows the efficiency curve for each case (MLR and DPI) for clear sky conditions, that is, $G_b = 850$ W/m² and $G_d = 150$ W/m², and the 95 % confident interval using the MLR results (black dot line). This figure shows the excellent agreement between both procedures for the entire temperature range, despite the large difference in second order loss factor a_2 .

Tab. 1: Value, uncertainty and t-ratio of the characteristic parameters of each parameter identification procedure.

Doromotor MLR					DPI	
Parameter	Value	Uncertainty	t-ratio.	Value	Uncertainty	t-ratio.
$\eta_{0,b}$	0.724	0.001	724	0.725	0.001	725
b_0	0.120	0.005	24	0.121	0.001	121
K _d	0.970	0.006	162	0.967	0.002	483
$a_1(W/m^2.K)$	4.244	0.114	37	4.172	0.029	143
$a_2(W/m^2.K^2)$	0.0085	0.0020	4.3	0.0099	0.0005	20
$a_5 (J/K.m^2)$	11020	565	20	11126	100	111



Fig 4. Efficiency curve for each parameter identification procedure.

Finally, to study the combined effect of the differences between the parameters, the useful energy produced by the collector was calculated for each case using eq. (1), assuming normal incidence and steady state, for different temperature and sky conditions. For the different sky conditions, the standard reporting Standard Reporting Conditions (SRC) given by the ISO 9806: 2017 standard were used, and results are show in Tab. 2 and Fig. 5. It can be seen that the difference in useful power is less than 0.2 % for all cases, that is, for all sky conditions and temperature differences.

Tab. 2: Useful power (W) produced by the collector for SRC.				
Blue sky	Hazy sky	Gre		
		10		

		Blue sky			Hazy sky			Grey sky	
(T T)	(G	b = 850 W/2	m²,	(G	= 440 W/z	m²,	(0	$G_b = 0 \text{ W/m}$	n ² ,
$(1_{m} - 1_{a})$	Gd	= 150 W/r	m ²)	Gd	= 260 W/r	m ²)	Gd	= 400 W/r	m ²)
	MLR	DPI	Dif.	MLR	DPI	Dif.	MLR	DPI	Dif.
0	1456	1457	0.1 %	1012	1013	0.0 %	567	566	-0.2 %
20	1278	1281	0.2 %	834	836	0.2 %	389	390	0.2 %
40	1086	1088	0.2 %	642	643	0.2 %	197	197	0.2 %
60	880	880	0.0 %	436	435	0.3 %	0	0	n.a.



Fig 5. Useful power (W) produced by the collector for SRC.

5. Conclusions

In this work we describe a specific implementation of a DPI procedure for the standardized quasi-dynamic testing of flat plate solar thermal collectors. This implementation was successfully validated against the standard MLR procedure. A complete description of the procedure and a freely accessible and explained code in Matlab was given in this paper, encouraging the use of this algorithm. The development of such a free and open algorithm represents an important basis for future research in the field of solar collector testing. A future work is the implementation of multi-node models and the comparison of their performance against the single-node model of the ISO 9806 (2017), attempting to improve the description of the use of this algorithm for other collector technologies, for instance, evacuated solar collector and unglazed collector.

6. Acknowledgments

The authors would like to thank the Ministerio de Industria, Energía y Minería (MIEM, Uruguay), especially its Dirección Nacional de Energía (DNE), the Fideicomiso Uruguayo de Ahorro y Eficiencia Energética (Fudaee, Uruguay) and the Corporación Nacional para el Desarrollo (CND, Uruguay), for having provided financial and logistical support for the development of the BECS facility and for having promoted this project with local capacities. The authors are also grateful to the PTB of Germany for promoting and financing the inter-laboratory on efficiency test of solar collectors, which has given us technical certainty about our local testing capabilities.

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H-06. Performance Measurement and Assessment

Performance Simulation and Monitoring Methodology of a Solar Cooling Installation in Aqaba, Jordan

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Abstract

This work presents the results of the energy performance simulation of a solar cooling system that is currently under installation in the Aqaba Chamber of Commerce office building in Jordan, as well as the monitoring methodology for the system's operation. The main components of the system are the flat plate solar thermal collectors (160m²), the single-effect absorption chiller (35kW), the two hot water storage tanks and the chilled water storage tank. The solar thermal cooling system is coupled with the existing central cooled water system and it is designed to cover approximately half of the cooling load of the building. Key Performance Indicators of the specific solar cooling system are defined and provide the basis of the monitoring system. Key Performance Indicators are defined according to IEA-SHC Task 38 and regard the solar field efficiency, the thermal and electrical coefficient of performance and the cooling solar fraction. The simulations show that the thermal energy produced by the collectors' field is 131,103 kWh/y, the cooling energy production is 79,525 kWh/y and the auxiliary electricity consumption is 4,979 kWh/y. The efficiency of the solar field is estimated at 0.38. The solar cooling system can cover the 0.52 of the building's cooling energy demand. The simulated thermal coefficient of performance of the whole solar cooling system is 0.61 and its electrical counterpart is 15.5. The simulation are reasonable, indicating that the correct design of the system and dimensioning of the components produce a well operating system with high energy saving potential.

Keywords: solar cooling, absorption chiller, energy simulation, solar fraction.

1. Introduction

Today, heating and cooling consume the most energy of all end uses, accounting for nearly half of global final energy consumption. The energy consumed for heating and cooling is a significant contributor to air pollution and carbon dioxide emissions, since the 77% of the heating and cooling demand is met by fossil fuels and non-renewable electricity (IEA 2020, IRENA 2021a).

Due to global warming, cooling and refrigeration demand is under rapid growth and several hundred million air conditioning units are expected to be sold per year by 2050 (IEA 2021). Indeed, by that date, the 37% of the electricity demand growth will be due to the growth of cooling and refrigeration demand. An enormous potential for cooling systems that use solar energy arises.

A major argument for using solar thermally driven cooling systems, instead of other technologies, is that they consume less conventional energy and use natural refrigerants, as appointed by the European F-gas Regulation (EU, 2014). But their most important advantage is that they can deliver cooling during the peak demand in summer. Therefore, purchase of electricity at its highest cost is avoided. In this way, solar thermal cooling reduces peak electricity demand and this is particularly important for countries with significant cooling loads (IRENA et al 2020). Additionally, solar thermal cooling can easily store heat and thus, shift the demand. These assets enable solar thermal cooling systems to reduce the electric demand for cooling in a building by more than 80%, compared to conventional cooling and air conditioning equipment (IEA 2021).

The market of solar thermal collectors is well established and growing; the global solar thermal capacity of solar thermal collectors in operation has grown from 62 GWth (89 million m²) in 2000 to 501 GWth (715 million m²) in 2020 and the corresponding annual solar thermal energy yields amounted to 51 TWh in 2000 and 407 TWh in 2020. The translation into savings for 2020 are 43.8 million tons of oil and 141.3 million tons of CO_2 (IEA 2021). Especially in the MENA region (Israel, Jordan, Lebanon, Morocco, Palestinian Territories, Tunisia), the total capacity of glazed water collectors in operation in 2019 is 7,361MW_{th} in total or 96.1 kW_{th} per 1,000 inhabitants. In terms of market penetration per capita, China is the leader, but MENA countries are remarkably ahead of Europe and Australia (IEA 2021).

Despite the clear advantages of solar thermal cooling, it is still a niche market, with about 2,000 systems deployed globally as of 2020 (IEA 2021). The main barriers of the limited market uptake can be attributed to costs, technical limitations and the need for further research and development (IRENA et al 2020). Even today, solar cooling technology is relatively expensive when compared to most electric alternatives. Finally, limited awareness of available technology options, their maintenance requirements and potential benefits impede their deployment.

At the same time, the legally binding international treaty on climate change "Paris Agreement" for limiting global warming by 2050 to 1.5°C (UNFCCC, 2015) can be only achieved through the energy transition grounded in renewable sources of energy and efficient technologies. But for the moment, the speed of this energy transition falls short of the 1.5°C goal (IRENA, 2021b). Especially for the Sun Belt countries, solar thermal energy has great potential to contribute towards decarbonisation of energy intensive processes, thus ensuring a rapid decline in emissions and contributing to net zero emissions by 2050.

This work aims at unveiling the energy saving of a solar cooling system, by presenting the energy performance simulation results for a typical office building in Aqaba, Jordan as well as the monitoring methodology for the system's operation. The results of this study are useful to mechanical engineers and companies designing and installing solar cooling systems, to manufacturers of solar cooling components, as well as to the final end users of the technology, especially in the countries of MENA region

2. Description of the Solar Cooling and Monitoring System

2.1. End User Description

The Aqaba Chamber Of Commerce Building is in Aqaba, Jordan and consists of a two-level basement, a ground floor and three floors of 450 m² each. The total air conditioned area is $1,848m^2$ at a cooling set point temperature 26.5°C. The building is occupied from 8:00 am to 3:00 pm from Sunday to Thursday. The building has no heating load. The cooling needs of the building, typically from March until October, are covered partially by two conventional vapor compression electric chillers, with total nominal capacity 344 kW (2*172 kW). The cooling energy of the building has been estimated at 146,510 kWh/y. The chillers are connected with a central piping network system (with estimated flow rate 5.5 m³/hr) distributing chilled water to the building, used for providing fresh air in the auditorium. Additionally, several autonomous air-conditioning split-units are installed in the building.

2.2. System Components

A solar cooling system will be installed in the terrace of the building and will be assisting the cooling production of the vapor compression chillers. The simplified system configuration is shown in Fig. 1. The solar cooling system was simulated with Polysun Designer (Polysun 11.2, 2020) simulation tool (Fig. 2). Considering the available free space in the terrace, the solar cooling system consists of the main following parts:

- 144 m² (aperture area) flat plate collectors
- 2 hot water storage tanks, 1,500lt each
- 35kW closed loop absorption chiller and
- 1 chilled water storage tank, 1,500lt that serves as the central chilled water provider for the air conditioning system of the building



Fig. 1: Solar cooling system configuration

The solar system operates every day during the cooling season, even when there is no occupancy or in weekends (Friday and Saturday). During these days without occupancy, the building turns into a 'solar only' mode, the solar system operates normally and chilled water is driven into the building in order to prevent excessive temperature increase and to retain the thermal comfort inside the offices. Two hot storage tanks are employed instead of one because there are height and space limitations in the site. The chilled water storage tank is not a standard subcomponent of solar cooling systems, but in the specific case it serves as a temporary storage to match the flow rates of the absorption chiller and the conventional vapor compression chiller. Therefore, its role is to facilitate the combination of the conventional chiller and the absorption chiller and not to store chilled water for a specific amount of time. This system is built in *Polysun* software, in order to elaborate the annual energy performance analysis.



Fig. 2: Solar cooling system simulated in Polysun software

The dimensions of basic components are shown in Tab. 1.

Tab. 1: Dimensions of basic components

Geographical data	Longitude: 35.01°, Latitude: 29.536°	
	Global irradiation, annual sum 2197 kWh/m ²	
	Diffuse irradiation, annual sum 542 kWh/m ²	
Flat plate solar thermal collectors	Area: 160 m ² gross, 144 m ² aperture	
	Tilt angle 25° (hor.=0°, vert.=90°)	
	Orientation 15° (E=+90°, S=0°, W=-90°)	
	Heat transfer fluid: 30% propylene glycol solution	
Thermal chiller cooling capacity	35 kW, absorption closed loop	
Hot water storage tanks	2 tanks, 1500 lt each	
Chilled water storage tank	1500 lt	
Cooling tower	Wet cooled, Cooling capacity 90kW	

2.3. Monitoring System

Monitoring of solar cooling systems is a fundamental tool to optimize the system operation and to enable the maximum energy yield with the minimum operational cost.

The designed monitoring system monitors the heat and electricity flow of all subsystems individually, according to the suggestions of IEA-SHC Task 38 (IEA, 2011). This procedure is performed by measurements of the temperature of the water in specific points, the water flow, the incident irradiation to the collector field and the electricity consumption of the components (pumps, fans, chiller, control). The aim of the monitoring process is to calculate the Key Performance Indicators (KPI) as defined in Tab. 2.

Key Performance Indicator	Equation
KPI 1 Solar Field Efficiency	Collectors' yield
	$n_{sf} = \frac{1}{Solar Irradiation onto collectors area}$
	This equation is relevant to the eq. 20 of the 2^{nd} monitoring level in IEA, 2011.
	Collectors' yield
	$Q_{coll} = m_{coll} * C_p * (T_{coll_out} - T_{coll_in}) kWh$
	Solar Irradiation onto collector's area
	Q_{irr} = Aperture * Global irradiation on tilted surface, kWh
KPI 2 Coefficient of Performance, Thermal	$COP_{th} = \frac{Cooling \ energy \ yield}{Heat \ supplied \ by \ storage \ tanks}$
	This equation is relevant to the eq. 57 of the 3 rd monitoring level in IEA, 2011.
	Cooling energy yield
	$Q_{cwt} = m_{cwt} * C_p * (T_{cwt_out} - T_{cwt_in}) kWh$
KPI 3 Coefficient of Performance, Electrical	$COP_{el} = \frac{Cooling \ energy \ yield}{Flectricity \ consumption}$
,	This equation is relevant to the eq. 59 of the 3^{rd} monitoring level in IEA 2011
	Electricity consumption = E_{Ptank} + E_{chill} + E_{ct} + E_{Pcoll} + E_{Pchill} + E_{Pct} + E_{pfc} , kWh
KPI 4 Solar Fraction, Cooling	$SF_{cool} = \frac{Cooling \ energy \ yield}{Building \ cooling \ demand}$
	This equation is similar to the eq. 11 of the 1 st monitoring level in IEA, 2011. The authors adjusted this relationship to convey the contribution of the solar energy to the building cooling demand. Therefore, there is a difference in the denominator: instead of using the primary energy demand, the authors have used the cooling demand of the building.

Tab.	2: Key	Performance	Indicators o	f the solar	cooling system
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The inputs necessary for the achievement of this monitoring procedure are listed below.

Tab. 3: List of monitoring	sensors and their position
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Name	Description
I _{amb}	Total irradiation on tilted surface, W/m ²
T_{coll_out}	Solar field outlet temperature (glycol), °C
T_{coll_in}	Solar field inlet temperature (glycol), °C
T_{chill_in}	Chiller inlet temperature from hot tanks (water), °C
T _{chill_out}	Chiller outlet temperature to hot tanks (water), °C
T _{cwt_in}	Chilled tank inlet temperature from chiller (water), °C
T_{cwt_out}	Chilled tank outlet temperature to chiller (water), °C
T _{amb}	Ambient air temperature, °C
F _{chill}	Water volumetric flow from chiller to tank, m3/hr
F _{cwt}	Water volumetric flow from chiller to chilled water tank, m3/hr



Fig. 3, where the additional sensors of the control system are also shown.



Fig. 3: Positioning of temperature sensors, flow rate sensors and valves for the monitoring and control system.

3. Energy Performance Results

Tab. 4 shows the annual values of the energy performance simulation results. The annual irradiation reaching the whole collector field is 347,892 kWh and the thermal energy produced by the solar collectors (total annual field yield) is 131,103 kWh, so the efficiency of the solar field becomes $n_{sf} = 0.38$.

Regarding the chiller performance, the total annual cooling energy yield is 79,525 kWh. The net energy subtracted from the building, through the fan coil cooling modules, is 76,687 kWh. This value includes the heat losses from the delivery system and components. Taking into consideration that the annual cooling energy demand of Aqaba Chamber of Commerce office building is 146,510 kWh, the SF_{cool} becomes 0.52, meaning that the solar cooling system can cover the 0.52 of the building's cooling energy demand.

The annual electricity consumption for the operation of the whole solar system is 4,979 kWh, 273 kWh of which are attributed to the electricity consumption of the pumps.

Solar thermal energy	
Global irradiation, annual sum	2,197 kWh/m ²
Irradiation onto collector area	347,892 kWh
Total annual field yield	131,103 kWh
Collector field yield relating to gross area	819.4 kWh/m ² /Year
Collector field yield relating to aperture area	910.4 kWh/m ² /Year
Thermal chiller	
Cooling energy demand	146,510 kWh
Heat supplied by generator	106,030 kWh

Tab. 4: Energy Performance Simulation Results

Total cooling energy yield	79,525 kWh
Net energy from/to heating/cooling modules	-76,687 kWh
System overview	
Total energy consumption	77,442 kWh
Total fuel and/or electricity consumption of the system	4,979 kWh
Total annual electricity consumption of pumps	273 kWh
Key Performance Indicators	
KPI 1 Solar Field Efficiency, n _{sf}	0.38
KPI 2 Coefficient of Perfomance – Thermal COP _{th}	0.61
KPI 3 Coefficient of Perfomance – Electrical COP _{el}	15.5
KPI 4 Solar Fraction in Cooling SF _{cool}	0.52

It has to be noted here that the KPI 3 and KPI 4 refer to the whole solar thermal system and not to the chiller alone. To evaluate the Coefficient of Performance, thermal and electrical, of the chiller only, then the equations become:

$$COP_{th_chiller} = \frac{Cooling \, energy \, yield}{Heat \, supplied \, by \, generator}$$
(eq. 1)

$$COP_{el_chiller} = \frac{Cooling \, energy \, yield}{Chiller's \, electricity \, consumption}$$
(eq. 2)

Accordingly, the COP values for the chiller only, considering the results of Tab. 2, are: $COP_{th_chiller}= 0.75$ and $COP_{el_chiller}= 2.91$.

Fig. 4 shows the annual distribution of the solar irradiation (yellow line), the yield of the total collector area (red line) and the cooling energy produced by the solar thermal chiller (blue line). This figure visualizes the solar system efficiency, which has been estimated at 0.38, as well as the thermal coefficient of performance of the system, which has been estimated at 0.61.



Fig. 4: Annual energy yields of solar cooling system

Fig. 5 provides the same energy yields with Fig. 4, but it focuses on an indicative week in July. The time coincidence of the curves show the smooth operation and control of the system; when solar irradiation becomes available, the system starts to operate, stores thermal energy and produces chilled water, which is either directly consumed or stored in the chilled water tank for future use. A small time lag is also obvious between the availability of solar energy and the chilled water production, which is reasonable.



Fig. 5: Energy yields of solar cooling system during a week in July

Fig. 6 shows the most important temperatures inside the system, during another indicative week, in June. The outdoor temperature reaches 45°C at midday and the indoor temperature is steadily slightly above 30°C. The maximum temperature of the collector is 109°C, but without observing any stagnation due to the specific technical characteristics of the selected solar thermal collector as well as due to the continuous heat consumption profile. The temperature of the hot water inlet to the absorption chiller follows the pattern of the collector outflow temperature, being slightly below it, due to heat losses. It is also seen that the temperature of the chilled water produced by the absorption chiller totally depends on the hot water inlet, being inversely proportional.



The system diagram along with simulated operation parameters for 29th March at midday, is shown in Fig. 7. The temperature output of the collectors is at 98.6°C. Due to heat losses and the presence of the heat exchanger, this is translated to 95.3°C inlet to the hot water tank. The system of two tanks has sufficient temperature stratification and seems to be working properly, since the right tank has higher temperature than the left tank. The hot water inlet to the thermal chiller is at 94.9°C. The hot water outlet from the chiller to the tanks is 85.7°C and corresponds with the lowest temperature of the left tank. The cooling water loop of the cooling tower, which is a crucial parameter at the design and dimensioning phase, is also working properly. The chilled water inlet to the building is at 7.2°C and the outlet is at 13.4°C, subtracting 58,559W from indoors.



Fig. 7: Solar cooling system state of operation in March 29th

4. Conclusions

Cooling and refrigeration demand is under rapid growth and several hundred million air conditioning units are expected to be sold annually by 2050, leaving enormous space for the market uptake of solar thermal cooling systems. Cooling and air conditioning through solar thermal energy has the outstanding advantage of time coincidence between supply and demand; thus enabling the reduction of peak electricity demand. Furthermore, they can inexpensively store heat and shift the demand, they use natural refrigerants and finally, they reduce the electric demand for cooling in a building by more than 80%, compared to conventional cooling and air conditioning units.

This study unveils the potential of solar cooling systems, by presenting the energy performance simulation results for a specific office building in Aqaba, Jordan. Key performance indicators of the specific solar cooling system are defined and provide the basis of the monitoring system. The monitoring system is in line with the requirements of 1st level monitoring procedure and consists of one irradiation sensor, seven temperature sensors, three flow meters and one electricity meter. The simulations showed that the thermal energy produced by the collectors' field is 131,103 kWh/y, the cooling energy production is 79,525 kWh/y and the auxiliary electricity consumption is 4,979 kWh/y. The efficiency of the solar field was calculated at 0.38. The simulated solar cooling system covers the 0.52 of the building's cooling energy demand. The thermal coefficient of performance of the whole solar cooling system is 0.61 and the electrical is 15.5. The results indicate that the correct design of the system and dimensioning of the system that includes acquisition of monitoring data and validation of the simulation results will be performed upon the completion of the installation that is expected to occur at the end of 2021.

5. Acknowledgments

This research has been carried out with the financial assistance of the European Union under the ENI CBC Mediterranean Sea Basin Programme and the MAIA-TAQA project.

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Semi-Virtual Dynamic Tests Of Hybrid Systems Coupling Solar Thermal And PV Panels With Heat Pumps

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Abstract

Considering the huge world's energy demand associated with heating and cooling (H&C), the share of installed renewable H&C solutions was still around 10% in 2018. In order to speed up a transition towards the widespread application of renewable H&C in buildings, innovative solutions must be designed to outperform traditional solutions by saving non-renewable energy. SunHorizon project is contributing to this effort by demonstrating optimized design and combination of commercial innovative solar (thermal or/and PV) and Heat Pumps (HP) technologies. In particular this paper aims to demonstrate how to evaluate experimentally two hybrid concepts, out of four in the whole project, that are coupling solar thermal and PV panels with heat pumps to satisfy thermal and electricity energy demand of residential buildings in Riga (Latvia) and Piera (Spain). Relying on the hardware-in-the-loop approach called TYPSS, specific short test sequences (TS) are created for each of the two Technology Packages (TP) that allow for extrapolation of the measurements to annual seasonal performance figures including electricity self-consumption, renewable heating and cooling indicators. Both hybrid systems reached experimentally 40% renewable energy ratios.

Keywords: performance test, hardware-in-the-loop, solar thermal, PV, PVT, heat pump, electricity self-consumption, renewable energy, building.

1. Introduction

Regarding the challenge of renewable energy integration for buildings H&C that is still around 5% of world's final energy use (REN21, 2021), the SunHorizon project proposal is to demonstrate innovative and reliable HP solutions (thermal compression, adsorption, reversible), properly coupled and managed with advanced solar panels (thermal, photovoltaic (PV) or hybrid PV and thermal (PVT)), to provide H&C to residential and tertiary building with lower emissions, energy bills and fossil fuel dependency. Four different TPs are being developed and demonstrated all across European climates (i.e. Germany, Spain, Belgium and Latvia) and building typologies (small and large-scale residential and tertiary buildings).

In this work, the wide SunHorizon scope above is restricted on two approaches, Hybrid System #1 (HS1) and Hybrid System #2 (HS2), which generate solar heat and electricity to save non-renewable energy consumption in residential context. HS1 can meet both heating and cooling demands rather in Mediterranean areas and will be operated in–situ in Piera (Spain). HS2 is focused on areas with predominating heating demand and will be installed and run in-situ in Riga (Latvia) from August 2021. The Sunhorizon objective is here to validate the technologies integration into HS1 and HS2 concept through the semi-virtual testing approach, essentially control aspects, with respect to the relevant operating conditions to be met afterwards on the real demo sites. The main new challenge of the test sequence elaboration compared to previous works context in Chèze et al. (2018) and Lamaison et al. (2021) is to address the challenging transition between heating and cooling seasons on the one hand, and the electricity balance between PV production and both system and building consumptions on the other hand while achieving satisfactory compromise between shortest sequences and estimation accuracy of extrapolated results regarding the annual simulation results.

The next section gives a description of the two different hybrid systems including the operation principle and the sizes of the components. Then the following section highlights the challenges for dynamic test bench when dealing with such hybrid systems and introduces the TYPSS methodology to elaborate customized test sequences.

Finally the results of the tests are presented for each hybrid system.

2. Hybrid systems

The challenges around hybrid systems definition and dynamic testing are relying on the diversity of system configurations and destinations. Indeed several technologies are available to use solar radiation for heat and electricity productions, as several type of heat pump, air-to-water or brine-to-water. In this work, we are relying on two examples from the SunHorizon project to illustrate this topic. A preliminary simulation work (Chèze et al., 2020) with TRNSYS dynamic system simulation software led to the design and sizing of HS2 and HS1 concepts and it's been used to develop the related dynamic system test conditions in the next section.

The HS1 concept illustrated in Fig. 1 is built from BDR Thermea products: separated 4 m² solar thermal flat plate and 10 m² PV panels with harmonized roof integration, air source reversible heat pump 6kW Coefficient Of Performance COP=3.4 at Air 2 / Water 35 °C, 300/140L buffer/domestic hot water (DHW) tank, and global controller managing heating/cooling and PV electricity balance at system and building level. The specific goal of this controller is to maximize PV self-consumption. To do so,the HP operation is forced when PV power is available. This way, PV power is stored as heat in DHW and buffer tank. The system is integrated in simulation in Piera (Spain) demonstration context: 110m² residential house with 2 people living in, 5.4 MWh space heating (SH) and 1.2 MWh space cooling (SC) demand supplied by radiators and fan coils separate circuits, 1.2 MWh DHW demand, 2.3 MWh electricity consumption. The estimation of the fractional Green House Gas savings (fsav,GHG) is 53% for HS1 in Piera compared to existing oil boiler and 4m² solar DHW heating system, also considering extra comfort gain through new cooling supply.



Fig. 1: Hybrid system HS1, solar thermal integration in parallel to heat pump thermal supply

The HS2 concept relies on 50m² Dualsun solar PVT panels, Boostheat 20kW thermal compression gas fired CO₂ heat pump with Gas Utilization Efficiency GUE=2.0 at A7/W35, 0.2/1.3 m3 cold/hot thermal storage tanks and 15kW SMart Electric heater (SmE) from PV electricity excess by Ratiotherm. The heat from hybrid PVT panels flows either to cold glycol tank or hot buffer tank, according to the coldest tank. The Boosheat unit is activated complementary to grant the supply of SH and DHW at the desired temperature. The evaporator is connected to the hottest heat source from outdoor air coil or mitigated glycol tank. The extra PV electricity produced by the hybrid PVT panels compared to building electricity balance is stored as heat into the buffer tank until 85°C temperature is achieved, then fed into the grid. The complexity is increased in this case by mixing components and controls from several manufacturers into new concept assembly for several demo sites and by mixing non-renewable gas and electricity consumptions to operate them. The HS2 system was integrated in simulation in Riga (Latvia) demonstration context: 108 m² residential house with 3 people living in, 13.3 MWh SH supplied by radiators and heating floor circuits, 1.6 MWh DHW, electricity consumption 7.2 MWh. The estimation of annual GreenHouse Gas emissions savings (fsav,GHG) through HS2 is 51% compared to the existing gas boiler.



Fig. 2: Hybrid system HS2, solar thermal integration in series/parallel heat pump thermal supply

3. Semi-virtual test of hybrid systems

3.1 Test bench integration

An illustration of the architecture of HS1 integrated in dynamic thermal sytem test bench laboratory is presented in Fig. 3, together with a picture of the indoor system parts. The specific part for this Hybrid sytem test is that the PV inverter was also simulated to send specific signals to the global controller, to maximize the PV selfconsumption.





Fig. 3: HS1 concept and outlook of real prototype integrated in semi-virtual test bench

The Fig. 4 is showing similar integration of HS2 into the semi-virtual test bench (pink) for the DHW module, separate radiators and heating floor SH modules, solar thermal hydraulic module, emulation of resistive temperature sensors of the virtual panels, indoor living room or outdoor air, or the outdoor air conditioning around HP's outdoor unit in the climatic chamber. Especially for the smart meter emulation regarding the management of virtual PV electricity instantaneous production (Wpv, dynamic variations influenced by HS2 real operating conditions), we need to calculate in eq. 1 the whole virtual building electricity balance (Wgridbal) in real-time (10s refreshing period) including the real system dynamic electricity consumption Welsyst in addition to the building electricity consumption profile (Welbuild) from the test sequence. The MODBUS TCP communication with Ratiotherm's controls allowed to emulate the Wgridbal value required to control the SmE self-consumption of PV excess and to log some controller's internal sensors and states for iterative controller's improvements.

Wgridbal = Wpv - Welbuild - Welsyst (eq. 1)

With Welsyst the electricity consumption sum of TIVA1 (RATIO controller), TIVA2 (Boosheat units) and TIVA4 (smart energy heater, also denoted below Wsmarth).





Fig. 4: HS2 concept and outlook of real prototype integrated in semi-virtual test bench

3.2 TYPSS methodology

The semi-virtual test is a global system test approach considering the real-time strong interactions between the building, the local energy systems and controllers, the environment and the users. In his PhD thesis work, (Sayegh, 2020; Sayeh et al., 2022) developed a new approach and automated tool called TYPSS (for TYPical Short Sequence selection). This generic methodology creates a short climate sequence from a dynamic model that reproduces the behaviour and the global performances of a system. The methodology is here applied to create the test sequence (TS) to be applied in real-time on the test bench to estimate the annual performances of the tested systems. This approach came after previous works following similar philosophy around the elaboration of short sequence test for dynamic thermal system test as in Albaric et al. (2010), Chèze et al. (2018), Menegon et al. (2020).



Fig. 5: Grouping method in typical day selection TYPSS

As illustrated in Fig. 5 and Fig. 6, the algorithm simulates a dynamic model similar to the target system with the short sequence, extrapolates and compares the outcomes with annual simulation criteria, subdivides the worst performing period (Different weight for each day of the sequence depending on the represented period length) until it finds the most appropriate day to represent each period. It iterates until each criterion is well estimated with the appropriate number of days for the sequence.



Fig. 6: Example of daily (left) and integrated (right) results for Backup Energy

In the SunHorizon work, the TYPSS tool was applied to the TRNSYS models of HS1 and HS2 to elaborate short test sequences that are relevant with respect to the two different demonstration sites and environments.

3.3 Application to Hybrid Systems

For the elaboration of HS1 short sequence, we selected the following six criteria as targets for the annual extrapolation process and we limited the target sequence duration to 10 days: WHP: HP electrical consumption, QDHW: DHW demand, QSH: SH demand, QSC: SC demand, WPV: PV electricity production, TBufTank: temperature of the buffer tank (H&C), referred in Tab. 1 and Tab. 2.

Fig. 7 illustrates two criteria involved in the TYPSS methodology to design a short sequence representative of one-year operation for HS1: the HP electricity consumption on the left hand-side (green), the average temperature of the buffer tank on the right hand side (blue). The evolution of both criterion for the annual sequence (solid line) and the TYPSS sequence (dashed line) is represented: daily values on the left part, cumulative values on the right side. One can see that the transition between the heating and the cooling season is well represented. The buffer tank is cooled during the appropriate period of the sequence and it represents an appropriate increase in the HP consumption during the summer period. With regard to the short 10-days sequence challenge, one can notice on Tab. 2 that the deviation of every criteria doesn't excess 6% except for the cooling load. It was decided an acceptable trade-off considering the short sequence duration requirement and higher priority given to the overall electricity consumption of the system.



Fig. 7: HS1 annual/10-days sequence comparison of HP electricity profile (left) and the buffer tank average temperature (right)

The Fig. 7 is showing relevant simulated HS1's dynamic behaviour looking at the daily consumption of the HP and the average temperature of the buffer tank indicator of the HC season. In the Tab. 1, annual key performance indicators (KPI) are well estimated by the extrapolated short sequence simulation results. The KPIs' definitions and assumptions regarding energy baselines of the existing system, country's primary energy coefficients and GHG emissions per energy carrier are detailed in SunHorizon public reports D6.1 (CEA et al., 2020).

Indicators	Annual sim.	Annual extrap. sim.
QSH - SH demand [kWh]	5442	5712
QSC - SC demand [kWh]	1105	1278
WHP - HP electrical consumption [kWh]	2342	2441
Fsav,PE - Primary Energy savings [%]	59%	62%

Tab. 1: comparison between annual and extrapolated short sequence indicators for HS1

RER - Renewable Energy Ratio [%]	42%	45%

Since no cooling demand in the HS2 case compared to HS1 case, we assumed that we need less criteria to represent the annual profile and we limited to three criteria and 9 days in the HS2 test sequence elaboration: the average flow temperature in heating floor and radiators (°C, criterion 1, Tflow), building electricity balance (KWh, criterion 2, Wgridbal) and the gas consumption (KWh, criterion 3, Qgas) presented in Fig. 8. In bottom-right view it shows a few profiles of the resulting 9-days sequence that still mimic an annual variations of outdoor air (-9/20 °C), solar radiation (800 W/m² max) and building electricity demand (0.1/3.5 kW).



Fig. 8: HS2 comparison of annual/9-days sequence profile (left) and integration (right) – 9-days sequence outlook (bottom-right)

The Tab. 2 is summarizing the criteria's prediction accuracy for both HS1 and HS2 short sequences. The R² coefficients of determination close to 1 are showing good agreement of the short sequences' profiles with regard to the annual ones.

Test sequenc e	Duratio n	WHP	WPV	Wgrid bal	Qgas	Tflow	TBuf Tank	QDHW	QSH	QSC
HS1	10 days	R ² =0.98 , cumul. 5.7%	R ² =0.99 , cumul. 4.1%				R ² =0.99 , cumul. 2.5%	R ² =0.92 , cumul. 1.6%	R ² =0.94 , cumul. 0.6%	R ² =0.97 , cumul. 12.0%
HS2	9 days			R ² =0.98 , cumul. 4.4%	R ² = 0.95, cumul . 2.3%	R ² =0.98 , cumul. 1.0%				

Tab. 2: various criteria selection for the design of HS1 and HS2 short sequences

4. Test results analysis

4.1 Detailed timeseries analysis

The 10-days HS1 short sequence generated by TYPSS ran on the HS1 prototype installed on the semi-virtual test bench. In addition to the global performance criteria estimations presented in next section, such test can bring valuable in-sights of the real system behaviour compared to pure numerical studies since it implies real component interactions and real system operation.

For instance, in Fig. 9 showing the temperature in the virtual building's kitchen, in the SH and SC loop, in the Buffer tank and in the DHW tank during HS1 tests, it reveals the effect on various monitored variables of the different HS1 system's settings, named SEQ1 and SEQ2 where the PV self-consumption threshold was modified. This is useful for the manufacturer to learn how to tune the prototype and elaborate applications guidelines since wrong setups of such complex hydraulic and controllers of hybrid system could underperform. The comprehensive monitoring of the tested system provides precious operation details for further improvements. The temperatures, thermal and power transfers can be compared to the simulations to check if the system is working as expected. Finally, running several test sequences SEQ1 and SEQ2 allowed to compare the influence of different controller settings.





Fig. 9: HS1 results, detailed view analysis of self-consumption behavior

Now looking at timeseries from the test sequence (TS) run of HS2 in Fig. 10, we are able to perform various global or detailed analysis. Since the real system's component configuration from industrial partners differs from the component configuration assumed in simplified simulation model, one can track potential for improvements from the detailed timeseries by comparing the measurements with simulated behaviour. These improvements are often in the field of control.

On the top view we notice the 24h-conditionning time to let the system reach an average thermal state in heating season: it's done by running the last day of the test sequence before monitoring performance from day 1 to 9 which is from time 0 to 216 h. It is showing as well that the room temperature (TZFRAD and TZGFHF) comfort is achieved (23.5°C set point was assumed from the baseline study in previous steps of the project), and we notice also the solar passive gains (room temperature increase while heating circuit stopped and solar radiation) revealing good performance of building's envelope.

In Fig.10 mid view, this test also revealed the self-consumption dynamic behaviour, following the simulated PV electricity production. One notices an average power feed-in into the grid about 500W in this situation, from electricity balance signal Wgridbal_kW. This test allow to detect a hardware component failure in electric heater, revealed by the oscillations of Wgridbal. It revealed also the pgazPCI 3kW gas modulation limit of the thermal compression heat pump, which is oversized regarding the heat demand of Riga's building.

In Fig. 10, bottom view, cumul. solth graphics (black line is simulated system while blue line is measured one), this test is enabling to compare the cumulated solar thermal heat production of the real tested system with the simulated one. It was expected that solar heat is produced and flows into the glycol tank and evaporator (as the coldest temperature): the test revealed it was not the case for the actual tested system, meaning significant deviation between the real system and simulation model.





Fig. 10: HS2 results, 9-days TS detailed views analysis - room heating temperatures (top), energy flows (mid), solar heat (bottom)

4.2 Annual extrapolation

Another perspective on the results offered by the TYPSS methodology is the extrapolation of the daily cumulated indicators to annual indicators with weighting factors from the test sequence elaboration.

For HS1, the Fig. 11 reveals rather good agreement for most of the indicators. As there was not room thermostat control, we noticed more thermal load, heating and cooling, that caused more HP electricity consumption.

From SunHorizon project perspective, the Tab.3 is presenting some of the calculated KPIs for both simulated and tested system. For the latter case, KPI are based on the extrapolated energy balance (including the Non Renewable Primary Energy consumption: PEnren) which is compared to the same baseline primary energy consumption (PEnren), including all building's thermal and electricity demands. The primary energy savings (Fsav,PE) reaches nearly 50%, GHG savings (Fsav,GHG) 43%, 40% of building energy demand comes from renewable energy (RER: Renewable Energy Ratio) and 66% electricity self-consumption (SCR: Self Consumption Ratio).

From the observed deviation between simulation and tested system, the next step would be to refine the modelling of HP's control to let both simulated and real prototype converge towards each other and reach increased savings.



Fig. 11: HS1 real/model comparison of extrapolated annual energy deviations

Tab. 3: HS1 real/model comparison of extrapolated annual KPIs

	PEnren baseline MWh	PEnren MWh	Fsav,PE	Fsav,GHG	RER	SCR
SIM	14.1	5.2	62%	56%	43%	41%
TEST		7.4	49%	43%	40%	66%

In the Fig. 12 for HS2 test, we notice again that the solar thermal heat production and evaporator loop are very low which caused increased gas consumption as previously detected in Fig. 10. It requires parameter settings adjustment to match the separate controllers' logics of solar loop and heat pump's loop (coming from two different manufacturers). We may also notice significant heating floor overheating that is possible since it is not controlled with room thermostat compared to the radiator area.

The Tab. 4 is showing significant primary energy and GHG savings but large deviations with expected values which requires further developments as more integrated controls to improve the solar thermal use at HP's evaporator.



Fig. 12: HS2 real/model comparison of extrapolated annual energy deviations

	PEnren baseline MWh	PEnren MWh	Fsav,PE	Fsav,GHG	RER	SCR
SIM	27.9	13.3	52%	54%	56%	88%
TEST		18.9	32%	41%	43%	85%

Tab. 4: HS2 real/model comparison of extrapolated annual KPIs

Looking at the two different systems and contexts, we notice that HS1 achieve highest PE/GHG relative savings scores that can use full potential renewable electricity from PV in cooling season vs. mixed gas and electricity HS2 case whenever it can rely on higher solar areas and thermal storage. On the other hand, HS2 that is mixing gas and electricity grid supply, with the flexible integrated smart electric heater and larger power-to-heat thermal storage manages highest PV electricity self-consumption score. We should refrain from direct comparison between HS1 and HS2 results since different energy baseline, different solar collector field's and heat pump's sizes and types, different climates and building demands, different country primary energy factors.

5. Conclusion

As a conclusion, thanks to the TYPSS methodology and tool, this work managed to develop a custom short test sequence for each system and demonstration environment, as customized building type, climate and users behaviours (DHW and specific electricity consumption). The test sequences allowed the extrapolation of the measurements during either the 10-days or 9-days tests to annual performance figures. The semi-virtual tests of real HS1 and real HS2, first prototype assemblies, with the TYPSS short test sequence proved for both more than 40% GHG savings coming from more than 40% renewable energy. It means that such hybrid systems can actually support increasing the current 10% renewable energy in H&C energy demand (REN21, 2021). The execution of both HS2 and HS1 tests revealed some tricky issues around the configuration of the controllers to achieve expected behaviours, like the PV self-consumption threshold setting for HS1. In particular for the HS2 system which is combining the components and controllers from two manufacturers, Ratiotherm and Boostheat, it revealed limitations around the integration of solar heat from PVT panels at the evaporator of the CO₂ heat pump and thus significant potential of performance improvement through further development. In addition, we noticed that the global performance of such real hybrid solar systems, alike for other traditional thermal systems, is overestimated if the heat pump is oversized with regard to recent high performance building even in cold climate. This testing experience allows issuing recommendations for the future reliable installations on-site in October 2021. The TYPSS methodology was demonstrated to be flexible to deal with the characterization of hybrid solar thermal and PV system and could address successfully the evaluation of other hybrid systems structure with batteries and Energy Management System (EMS) for instance.

6. Acknowledgments

The SunHorizon project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement N. 818329.

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Demonstration of a domestic photovoltaic-thermal (PVT)-heat pump system, performance simulation, and economic analysis for different climates

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Abstract

In recent years, there has been a growing interest in heat pumps coupled with photovoltaic thermal (PVT) collectors to cover the space heating and domestic hot water demand in buildings. However, most existing systems have not been designed for the specific heat demand of the climate they are located, and limited system comparisons have been conducted regarding performance and economy in different locations. In this study, the performance of a domestic PVT heat pump system installed in Denmark was demonstrated. A TRNSYS model of the system was created and validated with experimental data from the demonstration system. Afterward, it was used to perform a sensitivity analysis on the collector area to achieve the best performance and economy, using multiple indicators. Three different systems were investigated in three locations: a PVT water-source heat pump system, a photovoltaic (PV) air-source heat pump system, and an air-source heat pump system in Denmark, Austria, and Greece.

Keywords: Solar-assisted heat pump, TRNSYS, space heating, domestic hot water, PVT

1. Introduction

In Europe, almost 30% of the total energy consumed is used for space heating (SH) and domestic hot water (DHW) production. As of 2017, 9% of the energy used for SH and DHW is supplied by district heating (DH) (Fraunhofer Institute ISI, 2017). In Denmark, DH delivers heat to more than 60% of residential consumers (Danish Energy Agency, 2017). However, DH is not always available or feasible; hence, many consumers rely on individual oil, gas, and biomass boilers or heat pumps. For consumers who do not have access to DH, heat pumps are encouraged. They have generally been considered an efficient and sustainable solution since a large share of Denmark's electricity production comes from renewable energy sources (Danish Energy Agency, 2017).

Historically, ground and air source heat pumps have dominated the market. However, several manufacturers have developed hybrid Photovoltaic-thermal (PVT) collectors specifically for coupling with heat pumps in recent years. An advantage of PVT collectors is that they can produce electrical and thermal energy simultaneously (Aste et al., 2014). Like solar thermal (ST), PVT collectors can be coupled to heat pumps for covering the SH and DHW demand in buildings and are usually referred to as solar-assisted heat pump (SAHP) systems. PVT or ST collectors are typically connected to the source side of the heat pump, resulting in a higher source temperature, which increases the Coefficient of Performance (COP) of the heat pump, leading to lower operating costs (Pärisch et al., 2014).

Several studies have investigated SAHP systems, comparing systems located in different geographical locations, agreeing that PVT systems are attractive regarding performance and economy in countries with high solar irradiance and high ambient air temperatures (Fine et al., 2017; Ramos et al., 2017). However, in most of these studies, a sensitivity analysis of the system has not been performed, so it is unclear if these systems are optimized for the specific heat demand of the climate they are located. Proper dimensioning of the system's components has been proven very important for the performance of a system. A study performing sensitivity analyses on SAHP systems found that appropriate sizing of the system components can dramatically affect the system's performance, improving thermal performance by 18% and electrical performance by 50% (Dannemand et al., 2020).

This study aims to evaluate the performance of a pilot DHW and SH system consisting of building integrated PVT collectors connected to a water-source heat pump. A techno-economic analysis was carried out through simulations, where the system components were varied in size, and key performance indicators (KPIs) were calculated. Following this, the KPIs of the pilot system were compared to a system with an air-source heat pump and PV panels and a reference system with an air-source heat pump. Further, the analysis included simulations of these systems for the Northern, Central, and Southern European climate, elucidating the strengths and weaknesses of each system in each climate. Such studies are limited to the authors' knowledge, despite their great interest in industry and academia.
2. Methods

Initially, the performance of a pilot PVT – heat pump system was investigated. Afterward, a model of the pilot PVT – heat pump system was created in TRNSYS 18. The model's performance was compared to the measurements from the pilot system to have the model perform as close to the existing system as possible. Subsequently, a sensitivity analysis of the size of the PVT area was performed using reference year weather data. The results were compared to a reference system with an air-to-water heat pump and an alternative system where the air-to-water heat pump was coupled to PV panels. The comparison was made in terms of performance and economy for three different locations in Europe, namely Denmark, Greece, and Austria.

2.1 Pilot system description

The system under investigation was a roof-integrated PVT – heat pump system installed in a row house in Ølstykke, Denmark (55.777° N, 12.169° E). The 101-m² house was built in 1983 and was the residence of a four-person family. The PVT – heat pump system was installed as part of a completed demonstration project. The performance of the investigated system was monitored for a period of seven months, from January to July of 2019. However, the system is still in operation until the time of writing.

The system consisted of a building integrated PVT roof with a 25° tilt, shown in Fig. 1(a), connected to a heat pump. On the south side of the roof, 16 unglazed PTV panels were installed with an area of 48 m², along with four dummy panels to achieve a consistent aesthetic result. The PVT panels installed on the roof are numbered in Fig. 1(a) to be more visible. Two of these 16 panels were not in operation (panel numbers 5 and 13); thus, the active PVT area was 42 m^2 , corresponding to 14 panels. The PVT panels were south-west oriented (192° from the north) and were installed in seven rows of two in parallel. On the north side of the roof, 16 PV panels were installed, but they were not included in this study since they were not in operation during the monitoring period of the system. Fig. 1(b) illustrates a schematic of the system under investigation.



Fig. 1: Aerial photo of the roof integrated PVT panels (a) and schematic of the pilot system (b).

2.2 System control

The system was controlled through the following parameters and settings:

- The heat pump was set in operation when it had to charge the DWH or the SH tank. Charging of the DHW tank always had priority over the SH tank.
- The DHW tank was charged when the bottom temperature was lower than 44 °C and stopped when the top was higher than 59 °C.
- The SH tank was charged when the top temperature was lower than $SH_{setpoint} 4$ K, and charging stopped when the bottom temperature was higher than $SH_{setpoint} + 4$ K.
- The SH_{setpoint} was based on the ambient temperature (T_{amb}) and was calculated from the following equation:

$$SH_{setpoint} = 51.42 - 0.4025 \cdot T_{amb} - 0.0197 \cdot T_{amb}^2 - 7 \cdot 10^{-4} \cdot T_{amb}^3$$
(eq.1)

Equation (1) was obtained by least-square fitting a third-order polynomial to the manufacturer-specified space heating setpoints as a function of temperature. The space heating temperature set points were obtained through the online heat pump website portal. The described control strategy was implemented in the developed TRNSYS model

of the system.

2.3 TRNSYS model

A simulation model of the pilot system was developed in the simulation software TRNSYS 18. The model was validated with measurements for two weeks, namely from 14/2/2019 to 28/2/2019. The reason for choosing this period was that since the system was located in an inhabited house and was observed remotely, there were many situations where technical errors occurred during data acquisition, leading to very few periods with data available for all the components. The two weeks in February were the longest continuous period with all data available, and thus it was selected for model validation. An overview of the TRNSYS model is presented in Fig. 2.



Fig. 2: TRNSYS model of the system.

For modeling the PVT collector, TRNSYS component Type 835 (Danny, 2018) was used to simulate the electrical output, and Type 832 (Haller et al., 2012) was used to simulate the thermal output. Type 832 calculates the thermal output using the coefficients from the Quasi dynamic modeling method, as described in ISO 9806:2017 (International Organization for Standardization, 2017). In addition, it calculates the mean temperature of the collector fluid in the absorber, which is then given as input to Type 835 to calculate the PV cell temperature and thus the electrical output of the collector.

Since the panels were installed in parallel, in seven rows of two, in the TRNSYS model, for the ST part, the output of one row of collectors was simulated and multiplied by seven to get the output of all seven rows. The available measurements of weather conditions were limited, and only the total irradiance in the collector plane and the ambient temperature was available. The parameters for simulating the PVT collectors are presented in Tab. 1. It can be noticed that the used heat loss coefficient is significantly higher than typical values in the literature, where the heat loss factor is around 13 W/m²K for unglazed PVT collectors (Lämmle et al., 2017). This increased value was used because it included the heat losses caused by the wind. Since the PVT collectors were unglazed, heat losses due to wind were significant. However, wind measurements were not available on-site, so their effect was incorporated in the heat losses.

Tab. 1: Parameters used for modeling of PVT collector used in Type 835 and Type 832.		
Parameter	Value	Unit

Parameter	Value	Unit
Optical efficiency	0.54	-
Linear heat loss coefficient	18	W/m^2K
Effective thermal capacity	60	kJ/m ² K
Electrical efficiency at reference conditions	0.18	-
Temperature coefficient of solar cell efficiency	-0.4	%/K
Irradiance dependence of PV efficiency	-0.00035	W/m^2K

The TRNSYS component Type 927 was used to simulate the heat pump operation. A TRNSYS component for simulating the operation of a water-to-water modulating heat pump does not exist at the time of writing. For this reason, the modulating operation was modeled using a scale factor for regulating the heat pump capacity according to the desired output temperature and the inlet temperature of the source and load side, as is suggested in the literature (Dannemand et al., 2020). In addition, a constant electricity consumption of 22 W per hour was added to the

consumption of the heat pump to account for standby operation and electricity consumption of the circulation pump. Last, using an equation in TRNSYS, the source temperature entering the heat pump was limited to 20 °C, to account for the actual heat pump operation.

The DHW tank was simulated using TRNSYS Type 340, having a volume of 180 L and a height of 1.3 m. These values correspond to the actual dimensions of the DHW tank in the pilot system. The cold-water inlet was located at the bottom of the tank, and the DHW outlet at the top. The heat loss coefficient was set to 2 W/K for the top of the tank, 1.7 W/K for the sides, and 1.2 W/K for the bottom. These values were set so that the measured energy consumption for DHW matched the value obtained from the simulation. The HP charged the tank through a spiral heat exchanger.

A similar procedure was used for simulating the SH tank where Type 534 was selected, having a volume of 100 L and a height of 1.2 m. The heat losses were set to 2 W/K for the top of the tank, 1.6 W/K for the sides, and 1.1 W/K for the bottom. The SH tank was charged directly from the heat pump without the use of a heat exchanger. Hot water was taken from the top of the tank and supplied to the SH loop, while the loop's return was inserted in the bottom.

Both tank components divide the tank volume into a finite number of isothermal nodes, where each node is affected by fluid conduction, temperature inversion, and inlet/outlet flows. Stratification within the tanks is determined by the temperatures supplied to the tank and the number of nodes specified. The number of nodes for each tank was chosen based on the best results when comparing the outlet temperature. This resulted in 100 nodes for the DHW tank and 50 nodes for the SH tank, corresponding to 1.2 L and 2 L per node, respectively.

The system's thermal capacity and heat losses were modeled with 22 m of pipe on the source side of the heat pump (12 m exposed to outdoor ambient temperature and 10 m to indoor) and 1 m pipe connecting the heat pump with each tank.

2.4 TRNSYS model for yearly performance

The yearly simulation was performed using the Meteonorm weather files in TRNSYS. The SH setpoint was calculated from the ambient temperature, as described in equation (1). The SH heat load was 6 kW at an outdoor temperature of -10 $^{\circ}$ C and 0 kW for 18 $^{\circ}$ C or higher.

The DHW profile for the annual simulation in TRNSYS was created using the software DHWcalc from IEA Task 26 (Jordan and Vajen, 2001). The software generates daily DHW profiles by distributing DHW draw-offs throughout the year according to a probability function (Jordan and Vajen, 2000). The draw-offs are not identical for each day, whereas the total water volume is the same. In the yearly TRNSYS simulation, the daily DHW draw-off was set to 120 L, a typical value for a single-family house in Denmark.

2.5 Investigated scenarios

A sensitivity analysis was performed on collector areas ranging from $10 - 40 \text{ m}^2$ to identify the PVT area that gives the best performance and economy for the pilot system. The heat pump of the pilot system was oversized; thus, smaller heat pumps were investigated in the simulations. Assuming that the ratio of the minimum load to the nominal capacity is 20 - 30% for most modulating heat pumps, a heat pump of 1.2 - 6 kW was considered most appropriate for Denmark and Austria and 0.9 - 4.5 kW for Greece.

In general, it is a common practice to use an oversized heat pump in domestic heating systems. Typically, a heat pump would be selected so the nominal capacity can match the building heat demand on the coldest day in the region. This forces the heat pump to operate in part-load capacity most of the time and minimizes the chance of direct electricity consumption through the auxiliary electrical heater, potentially resulting in a higher Seasonal Performance Factor (SPF) of the system (Zottl et al., 2012). However, in the pilot system, the minimum capacity of the heat pump was larger than the maximum heating load, so this principle was not fulfilled, as shown in Section 3.1.

The PVT-heat pump system was compared to a reference system and a PV-air-heat pump system. The reference system consisted of a modulating air-to-water heat pump (Type 509b: Variable Speed Compressor Air-to-Water Heat Pump), and the load side of the heat pump, storage tanks, and the control of the system remained the same. For simulating the heat pump, the performance map of Daikin Altherma ERLQ006-CV3 was used (Daikin, n.d.). The capacity of the air-to-water heat pump was the same as the water-to-water for the investigated locations.

The PV-air-heat pump system had the same heat pump as the reference system and 40 m² of PV collectors, able to supply electricity to the heat pump and the household. A sensitivity analysis on the PV collector area was performed, varying the collector area from 10 - 40 m², but only the best performing scenario is presented in this study for space-saving purposes.

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2.6 Key Performance Indicators and economic analysis

To assess the system's performance under investigation, selected key performance indicators (KPIs) were calculated, giving simplified information about the system's performance. The International Energy Agency – Solar Heating & Cooling Programme – Task 60 recommended the indicators used (IEA SHC Task 60, n.d.) and are presented in Equations (2) - (8). The term heating system (*HS*) refers to the entire system under investigation except for the PVT panels.

The **net solar electrical fraction** is the ratio of electrical energy produced by the PVT, E_{PVT} , relative to the sum of the electricity consumed by the heating system and household, $E_{HS}+E_{HE}$.

$$f_{sol,el}^{net} = \frac{E_{PVT}}{E_{HS} + E_{HE}}$$
(eq.2)

The **seasonal performance factor** (*SPF*) is the thermal energy produced by the heating system, Q_{HS} , divided by the electrical energy from the grid used by the heating system $E_{grid,HS}$.

$$SPF = \frac{Q_{HS}}{E_{grid,HS}}$$
(eq.3)

The electricity self-consumption fraction is the ratio of the directly consumed PVT-generated electricity by the heating system and the house, $E_{PVT,HS} + E_{PVT,HE}$, to the total electricity production of the PVT, E_{PVT} .

$$f_{self,el} = \frac{E_{PVT,HS} + E_{PVT,HE}}{E_{PVT}}$$
(eq.4)

The **levelized cost of energy** (*LCOE*) measures the average net present cost of energy generation for a system over its lifetime. It is calculated as the ratio between the costs over the system's lifetime to the sum of the energy delivered.

$$LCOE = \frac{I_0 + \sum_{t=1}^{LT} (OM_t - RV_t - E_{PVT,grid,t} \cdot P_{el,sale,t} - E_{PVT,HE,t} \cdot P_{el,ret,t}) \cdot (1+r)^{-t}}{\sum_{t=1}^{LT} (Q_{HS,t} + E_{HE,t}) \cdot (1+r)^{-t}}$$
(eq.5)

Where I_0 is the initial investment cost, OM is the operation and maintenance cost, RV is the residual value, $P_{el,sale}$ is the price of electricity sold to the grid, $P_{el,rel}$ is the retail price of electricity, r is the discount rate, and LT is the lifetime of the system. In the *LCOE* expression, two things were accounted as income; the income from selling electricity to the grid and the savings deriving from the part of household electricity demand that the PVT collector covered.

The **payback period** (*PP*) corresponds to the time after which the financial savings achieved with the solar heating system compared to the reference system compensated for the additional investment for the solar heating system.

$$I_{0,sol} - I_{0,ref} = \sum_{t=1}^{PP} \left(\Delta OM_t + E_{PVT,grid,t} \cdot P_{el.sale,t} + E_{PVT,HE,t} \cdot P_{el,ret,t} \right) + \Delta RV_{LT}$$
(eq.6)

Where ΔOM_t is the difference between the operation and maintenance cost of the two systems.

$$\Delta OM_t = (OM_t)_{ref} - (OM_t)_{sol} \tag{eq.7}$$

And ΔRV_{LT} is the difference between the residual values of the two systems after their lifetime.

$$\Delta RV_{LT} = (RV_{LT})_{sol} - (RV_{LT})_{ref} \tag{eq.8}$$

2.7 Economic assumptions

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For calculating the economic performance indicators, the following assumptions were made:

- The OM costs were calculated based on the electricity price and the electricity consumption of the heat pump (operation costs), plus 1% of the total investment cost of the system (maintenance costs). It has to be noted that the exact OM cost of the system are not known.
- The lifetime of the investigated system was assumed to be 25 years, which was a reasonable assumption for a solar heating system according to IEA Task 54 (IEA Task 54, 2018). The residual value was assumed zero.
- According to IEA Task 54 (IEA Task 54, 2018), since the discount rate is normally taken equal to the weighted average cost of capital (WACC) and the total cost is paid upfront for single-family systems, the discount rate was taken at 0%.

• The household electricity consumption used was from an actual building in Denmark, corresponding to 3320 kWh/year. For simplicity, the same consumption was used for all investigated locations.

The costs of the individual components used in the investigated systems are presented in Tab. 2. These prices were based on indicative retail prices of these types of components in Denmark. The heat pump cost was assumed constant and independent of the heat pump capacity to simplify the calculations. The installed panels were integrated into the roof of the building, substituting the roof material. For this reason, an amount was subtracted from the investment cost of the installation due to less roof material used. The amount was based on the m^2 of panels installed.

Component	Cost	Unit	Source
PVT collector	268	€/m ²	Invoices sent to authors
PV collector	185	€/m ²	(Fina et al., 2020)
Heat pump (water-to-water)	8000	€	("PriceRunner," 2020)
Heat pump (air-to-water)	5400	€	(Daikin, 2017)
Pipes (including insulation)	10	€/m	(Wang et al., 2019)
Space heating tank 100 L	400	€	("VVS-Eksperten A/S," 2020)
Inverter	22.64 · A _G +658.43*	€	(Europe-Solarshop, n.d.)
Expansion vessel	100	€	Invoices sent to authors
Heat transfer fluid	3	€/L	(Wang et al., 2019)
Roof material saved	67	€/m ²	Supplied by PVT manufacturer

Tab. 2: Components' costs

* The price of the inverter is calculated based on the area of the panels (A_G). This expression was derived from prices of Fronius inverters (Europe-Solarshop, n.d.), assuming that a 2 m^2 PV panel produces 350 Wp.

2.8 Location description

Systems at three different locations were studied, namely Denmark, Greece, and Austria. For simplicity, the capital of each country was used for selecting the weather file in the TRNSYS simulation, namely Copenhagen, Athens, and Vienna. However, different electricity prices and labor costs for each country affect the economic indicators. In addition, the heating periods in the countries are different due to climate differences. The space heating load for each country was calculated based on the ambient temperature. The data used for each country are presented in Tab. 3.

Tab. 3: Data for each investigated country

	Denmark	Greece	Austria
Retail electricity price	0.31 €/kWh (Danish Utility Regulator, 2019)	0.18 €/kWh (HAEE, 2019)	0.21 €/kWh (European Commission, 2019)
Wholesale electricity price	0.055 €/kWh (EnergiNet, n.d.)	0.066 €/kWh (European Commission, 2019)	0.059 €/kWh *
Installation cost	20% of the component cost (high technician salaries)	7.2% of the component cost (64% lower labor costs than Denmark (Eurostat, 2019))	15.5% of the component cost (22% lower labor costs than Denmark (Eurostat, 2019))
Heating Period	15/9 - 15/5	15/10 - 15/4	1/10 - 30/4
Capital coordinates	55.676° N, 12.568° E	37.984° N, 23.728° E	48.208° N, 16.374° E
Mean yearly temperature	7.9 °C	17.6 °C	9.8 °C
Total horizontal yearly solar irradiation	989 kWh/m ²	1565 kWh/m ²	1112 kWh/m ²

* In Austria, residential PV systems larger than 5 kWp are supported for up to 13 years with an electricity selling price of 0.08 ϵ/kWh (Fechner, 2018). After that period, the price for selling electricity to the grid is 0.037 ϵ/kWh (European Commission, 2019). The weighted average is taken in this study for 25 years of operation.

3. Results

3.1 Pilot system performance

The PVT-heat pump system was able to cover the total heating demand of the house. The monthly energy



consumption for space heating and domestic hot water is presented in Fig. 3(a). As expected, the space heating consumption exhibited a clear seasonal trend, with lower heat consumption in the spring and summer months.

Fig. 3: Monthly energy consumption for DHW and SH (a) and mean daily SH consumption and outdoor temperature (b).

The mean daily SH consumption can be seen in Fig. 3(b). It can be observed that the mean SH load was very low compared to the size of the heat pump (3-12 kW). This indicates that the heat pump was oversized for this system, resulting in very short operation periods and relatively low heat pump efficiency. This is illustrated in Fig. 4(a), where the daily average COP of the system is presented. According to the manufacturer, the seasonal COP of the heat pump for a heating system with radiators in a cold climate (Helsinki) should be 4.3. However, for the investigated system, which was also a radiator heating system in a cold climate, a COP closer to 3 was obtained. This may be due to the oversized heat pump, which resulted in many start/stops within each day instead of continuous operation. This can be seen in Fig. 4(b), where the flow rate in the HP source loop, indicating HP operation, is presented for two days of operation. It can be observed that the heat pump had 15 to 17 operation cycles within one day.



Fig. 4: Daily average COP of the system (a) and heat operation for two days (b).

3.2 TRNSYS model validation

The TRNSYS model outputs are compared to measurements from the pilot system in Fig. 5. As it can be observed, there is generally a good match between the compared parameters. The bias between the measured and modeled values for the simulated period was around 2% for all investigated parameters. The corresponding bias for each parameter is presented in Tab. 4. In general, the results of the TRNSYS simulation were in good agreement with the measured data; thus, the model was considered accurate for describing the operation of the pilot system.

Tab. 4: Variation between the measured and the simulated parameters for the investigated period.

Parameter	Bias [%]
PVT collector thermal output	2.1
PVT collector electrical output	-2.1
Heat pump COP	2.2
DHW energy consumption	-2.3
SH energy consumption	-2.3



Fig. 5: Comparison of measurements from the pilot system and modeled values from the TRNSYS simulation.

3.3 System comparison

The performance indicators of the systems are presented in Fig. 6 and Fig. 7. A short description of each case, along with the economic indicators, are given in Tab. 5. The scenarios with the smaller heat pump sizes are referred to as "small" in the diagrams.

In Fig. 6, the net electricity fraction and the electricity self-consumption fraction are presented. As expected, when using smaller collector areas, the net electricity fraction was decreased while the self-consumption fraction increased. This happened because, although less electricity was produced, a larger fraction of it was used directly by the heating system or the household. The low wholesale electricity price encourages self-consumption of electricity; thus, all investigated cases maximized their profit for a self-consumption fraction of 50 - 60%. Higher self-consumption fractions were not favorable to the systems' economy since they occurred due to very low total electricity production.



Fig. 6: Net electricity and Self-consumption fraction of the compared systems.

The SPF of the investigated systems is presented in Fig. 7. The reference system had the lowest SPF among the

investigated systems, approximately 2 in Denmark and Austria and 3 in Greece. The main reason for this is that the entire electricity consumption of the reference system comes from the grid. In contrast, the PVT and PV systems have higher SPFs since the systems consume less electricity from the grid due to self-consumption. In addition, the air-to-water HP has a relatively low COP in cold climates, especially when the HP has to produce high-temperature output. It can also be observed that the PVT-HP systems in all investigated scenarios had higher SPFs than the PV-HP system. The reason is that in PVT-HP systems, the heat pump COP is increased due to the brine temperature increase through the panel. Lastly, the effect of the HP size is also illustrated in Fig. 7, where a smaller HP always increases the SPF of the system. The largest improvement of the SPF was in Greece, where a HP with approx. 60% lower capacity, increased the SPF of the system by 95%, due to optimal operation leading to lower electricity consumption but also high self-consumption of the system.

Although the PVT water-HP systems have larger SPFs than the PV air-HP system, they are less economically attractive, having higher LCOEs and PPs, as shown in Tab. 5. The reason is that the investment costs of the PV systems are lower since the price of PV modules is 30% lower than PVT modules, the air-to-water HP is 32% cheaper than the water-to-water and has a simpler, thus cheaper, installation.

In Tab. 5, it can be observed that LCOE was lowest in Greece, followed by Austria, and highest in Denmark. This indicates the effect of high installation costs and low solar irradiance on LCOE. Countries like Greece, with high annual solar irradiance and low installation costs, had lower LCOE than countries like Denmark with low solar irradiance and high installation costs, suggesting Greece is a more favorable location for installing SAHP systems.





However, Denmark has the highest retail price of electricity, making the savings deriving from electricity selfconsumption considerable. This leads to Denmark having the biggest difference between LCOE and LCOE_{ref} and thus has the shortest payback period among the compared countries. Greece and Austria have longer payback periods, with values exceeding the lifetime of the system in some cases.

A big difference is spotted when comparing the LCOE of the PVT system with the LCOE of the PV system for the investigated countries. It can be observed that the LCOE of the PVT system is just 10% higher compared to the PV in Denmark and Austria but 50% higher in Greece. This finding suggests that a PV air-HP is a more suitable solution for warmer climates where the air-HP has a higher COP. PVT water-HP systems show their potential in the colder climates, indicating that they could be the optimal option had the system's price been slightly lower. In this study, the PVT collectors were assumed approximately 30% more expensive than PV panels. However, if the cost of the PVT collectors was only 15% higher than the PV panels, then the PVT water-HP systems would have a marginally lower LCOE than the PV air-HP system in Denmark and Austria. This price decrease is considered a possible scenario for the near future, as the PVT technology is currently at a relatively early stage in development compared to the more mature PV technology.

Lastly, it has to be mentioned that the best performing SAHP systems have lower LCOE than the reference system in all countries, indicating that they are a more suitable choice than an air-to-water HP, regardless of the climate they are installed in.

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	System	Panel Type	HP capacity [kW]	HP type	LCOE [€/kWh]	PP [years]
	Reference system	-	1.2 - 6	Air-to-water	0.14	-
	40 m ² pilot system	$40 \text{ m}^2 \text{PVT}$	3 - 12	Water-to-water	0.13	19.4
rk	40 m ² small HP	$40 \text{ m}^2 \text{PVT}$	1.2 - 6	Water-to-water	0.11	16.4
nma	20 m ² small HP	$20 \text{ m}^2 \text{PVT}$	1.2 - 6	Water-to-water	0.11	13.9
Dei	15 m ² small HP	$15 \text{ m}^2 \text{PVT}$	1.2 - 6	Water-to-water	0.12	14.4
	10 m ² small HP	$10 \text{ m}^2 \text{PVT}$	1.2 - 6	Water-to-water	0.12	14.5
	40 m ² PV air-HP	$40 \text{ m}^2 \text{PV}$	1.2 - 6	Air-to-water	0.10	10.7
	Reference system	-	0.9 - 4.5	Air-to-water	0.08	-
	40 m ² pilot system	$40 \text{ m}^2 \text{PVT}$	3 - 12	Water-to-water	0.09	27.4
a	40 m ² small HP	$40 \text{ m}^2 \text{PVT}$	0.9 - 4.5	Water-to-water	0.07	20.4
ioee.	20 m ² small HP	$20 \text{ m}^2 \text{PVT}$	0.9 - 4.5	Water-to-water	0.07	19.4
G	15 m ² small HP	$15 \text{ m}^2 \text{PVT}$	0.9 - 4.5	Water-to-water	0.08	20.5
	10 m ² small HP	$10 \text{ m}^2 \text{PVT}$	0.9 - 4.5	Water-to-water	0.08	21.3
	40 m ² PV air-HP	$40 \text{ m}^2 \text{PV}$	0.9 - 4.5	Air-to-water	0.04	11.3
	Reference system	-	1.2 - 6	Air-to-water	0.10	-
	40 m ² pilot system	$40 \text{ m}^2 \text{PVT}$	3 - 12	Water-to-water	0.11	29.9
a	40 m ² small HP	$40 \text{ m}^2 \text{PVT}$	1.2 - 6	Water-to-water	0.10	21.7
stria	20 m ² small HP	$20 \text{ m}^2 \text{PVT}$	1.2 - 6	Water-to-water	0.09	19.6
Au	15 m ² small HP	$15 \text{ m}^2 \text{PVT}$	1.2 - 6	Water-to-water	0.10	20.7
	10 m ² small HP	$10 \text{ m}^2 \text{PVT}$	1.2 - 6	Water-to-water	0.10	21.0
	40 m ² PV air-HP	$40 \text{ m}^2 \text{PV}$	1.2 - 6	Air-to-water	0.08	13.5

Tab. 5: Levelized cost of energy (LCOE) and payback period (PP) of the investigated cases.

The LCOE indicator was used to select the best-performing system from a performance and economy perspective among the ones investigated. The reason for choosing LCOE is that it is affected by the system's performance. A lower electricity consumption or a higher electricity self-consumption would result in better performance and lower LCOE. The PP was taken into consideration in cases where two systems had the same LCOE. The best-performing PVT system had 20 m² of PVT area and a smaller HP for all three countries. Further, the study showed that the best-performing PV-HP system had 40 m² of PV area and a smaller HP and lower LCOE and PP than the optimal PVT system. The reason for the difference in panel area between the PVT and the PV systems is the lower price of PV panels and simpler, thus cheaper system installation. Nonetheless, it is clear that the capacity of the HP has to be chosen according to the load it has to operate, regardless of the climate it is installed.

It has to be mentioned that the selected optimal PVT systems did not have the best SPF in any of the investigated countries, contrary to the PV systems, indicating that economy is the main barrier for the PVT-HP systems. However, since the cost of the PVT panels has constantly been decreasing in the last years, it is believed that they will be the best option regarding both performance and economy for cold climates in the near future.

4. Conclusions

In this study, a domestic PVT water-HP system was demonstrated and optimized regarding economy and performance. The system was installed in a single-family house in Ølstykke, Denmark, and measurements from January to July 2019 were presented. A TRNSYS model of the system was created and validated with the measurement data. Afterward, yearly simulations were performed for three different locations, namely Denmark, Greece, and Austria. Three different systems were investigated for each location: a PVT water-source HP, a PV air-source HP, and an air-source HP system. The main findings from this investigation were:

• The best-performing PVT water-source HP system had 22% higher SPF in Denmark, 23% in Austria, and 50% higher in Greece than a PV air-HP system. However, the PV air-source HP system was the most favorable system when considering the economy. The LCOE was 10% lower in Denmark and Austria while 50% lower

in Greece. The main reason is that the investment cost of the PVT water-source HP system is much higher due to the more expensive panels, HP, and installation.

- PVT water-source HP systems have a greater potential in colder climates, where air-source HP systems have a lower SPF, indicating that they could be the optimal option had the system's total price been a little lower.
- In all investigated locations, the best-performing PVT water-source HP system had better performance and economy than the reference system, which was an air-source HP system. The PVT system had 63% higher SPF in Denmark, 64% in Austria, and 125% in Greece. Also, the LCOE was 20% lower in Denmark and 10% lower in Greece and Austria.
- Economy indicators (especially the payback time but also LCOE) improved with higher electricity selfconsumption. In general, it is observed that there is no financial benefit from selling electricity to the grid with the listed wholesale electricity prices.
- Proper dimensioning of the HP capacity and collector area is essential for achieving the best economy and performance. However, due to the price difference between the two systems, the selected area for the PV system was 40 m² while for the PVT, 20 m².
- If the price of the PVT collectors was only 15% higher than PV panels, instead of 30%, which was assumed in this study, then the PVT water-HP systems would have a marginally lower LCOE than the PV air-HP system in Denmark and Austria. This would lead to the PVT water-HP systems having the same, if not better, economy than the PV air-HP systems for cold climates.

In general, it can be stated that the main barrier of the PVT water-source HP systems is the price of the system since they had the highest performance among the studied systems. Since the PVT technology is currently at a relatively early stage in development compared to the more mature PV technology, it is expected that the price of the system will decrease in the future, making the PVT water-HP system the optimal choice regarding performance and economy in cold climates.

5. Acknowledgments

The research was financed by the Bjarne Saxhofs Fond.

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Study on Heating Performance of Solar Fresh Air Systems

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Abstract: Due to the global spread of COVID-19, indoor air quality has been paid more and more attention by many countries. However, the ventilation of buildings often causes a significant increment in buildings' heating and cooling load, especially in the winter of the Northern Hemisphere. Solar fresh air systems can provide heated fresh air to buildings on sunny days. This system can provide not only fresh air to buildings but also improve indoor air quality. At the same time, the heating load of buildings will be significantly decreased by the application of this new system. Solar fresh air systems can even take the existing heating energy source's place under high solar irradiation. The solar heating performance of the solar fresh air system is affected by many factors. The two most important factors are the structure of the solar heating panel and the performance of solar absorption coating on the solar heating panel. This research project has built three sets of real solar fresh air systems to test the influence of different solar absorption coatings and different solar heating panel structures on the heating performance of the solar fresh air system solar heating panel performance and solar heating performance of the solar fresh air system solar heating panel structures on the heating performance of the solar fresh air systems of stagnation performance and solar heating efficiency.

Keywords: Solar fresh air system, Solar heating panel, Stagnation performance, Solar heating efficiency

1. Test system introduction

Indoor heating is the most prominent single energy usage in most heating climates such as North America, Europe, and China [1]. Therefore, solar air heating is developed to provide an economical and applicable solution for heating and ventilation [3]. The panel structure and solar absorption coating are the most critical factor in this system [2]. This paper will compare the system stagnation performance and solar heating efficiency in different absorption coating and different positions. Three sets of solar fresh air systems are developed in Figure 1.



Fig. 1: Test system

1.1 External dimensions: three sets of solar fresh air systems in the test have the exact external dimensions:3 m in length, 2 m in height, and 15 cm in thickness of air interlayer.

1.2 Porosity of solar heating panel:1% for all three systems.

1.3 Structure of the solar heating panel: for System 1 and System 2, the front side of the solar heating panel is provided with solar absorption coating, and the backside is provided with heat emission coating. For System 3, the front side of the solar heating panel is provided with solar heat absorption coating, and the backside is not provided with heat emission coating.

1.4 Types of solar absorption coating: for System 1, the solar absorption coating is non-selective. For System 2 and System 3, the solar absorption coating is selective.

Project	System 1	System 2	System 3		
Length	3 m				
Height	2 m				
Area	6 m ²				
Thickness of air interlayer	15 cm				
Porosity of solar heating panel	1%				
Absorbance of frontal coating	0.944	0.937	0.937		
Emittance of frontal coating	0.899	0.452	0.452		
Emittance of back coating	0.899	0.908	None		

Tab 1: Parameters of test system

2. Test methods

2.1 Build the test system according to Table 1 and Figure 1.

2.2 Arrange temperature sensors in the same position of each system (the temperature sensors have been uniformly calibrated before installation), as shown in Figure 2.



Fig. 2: Distribution diagram of temperature sensors in the test system

2.3 The pipe size, fan type and installation position of the three test systems are precisely the same. The handheld anemometer is used for air volume measurement.

2.4 Acquire simultaneous ambient temperature and real-time solar irradiation on the south facade.

2.5 Total fifteen temperature sensors are adopted in three systems besides ambient temperature. The serial number can be found in Table 2.

	· ·		
Function	System 1	System 2	System 3
System top temperature	T1-1	T2-1	T3-1
System middle temperature	T1-2	T2-2	T3-2
System bottom temperature	T1-3	T2-3	T3-3
Panel temperature	T1-4	T2-4	T3-4
Air outlet temperature	T1-5	T2-5	T3-5

Tab 2:	Temperature	nosition	and	function
140 4.	remperature	position	anu	runction

3. Test result analysis

3.1 Stagnation temperature of air interlayer

It can be found that an air interlayer will be formed between the panel and the south building facade. The interlayer's highest temperature is defined as system stagnation temperature. The fan is turned off on a typical sunny day, then the temperature variation in the air interlayer is measured when the system has no heat output.



Fig. 3: Temperature changes in the air interlayer

It can be seen that System 2 has the highest stagnation temperature, followed by System 1 and System 3. System 2 always maintains good performance because it has a high-absorption coating on the front and a high-emission coating on the back. System 1 is compared with system 3, the temperature rise of system 3 is faster before 10 a.m. After that, system 1's temperature is always higher than system 3, which shows that the high-emission coating on the back can effectively increase the heat gain of the solar fresh air system.

After three days of operation, the interlayer temperature always reached the maximum at noon. The highest temperature of System 1 with the double-sided coating is 53 °C, while System 2 is 50 °C and System 3 has the lowest temperature of 49 °C.

3.2 Solar heating efficiency

Turn on the fan on a sunny day. The solar energy will turn to heat energy and be sent indoors by a fan. The temperature rise in the three systems is shown in Figure 4.



Fig. 4: Temperature rise comparison in three different systems

It shows that the temperature rise of the System 2 and System 3 using solar selective absorption coating is significantly higher than System 1 using non-selective coating when the solar radiation is low, indicating the use of selective coating can effectively improve the heat efficiency of the solar fresh air system in the morning, evening and windy days, which thereby increases the solar energy utilization rate of the system throughout the year.

Comparing System 2 and System 3 with the same selective absorption coating, System 2, which has a high-emission coating on the back, always performs better than the temperature rise of System 3 without the high-emission layer.

The temperature in the low irradiation period will only preheat the air interlayer, which cannot be sent to the building. Meanwhile, the efficiency should be tested as a quasi-steady state. Therefore, the data between 10:32 a.m. and 11:54 a.m. is chosen for analysis and calculation. The solar irradiation can be seen in Figure 5.



Fig. 5: Facade solar irradiation

The facade irradiation stability is in good condition during this period, with the minimum and maximum values of 714 W/m² and 736 W/m², respectively. The fluctuation is no more than 20 W/m². The ambient wind speed is about 1 m/s, which belongs to low wind speed weather.

The air energy brings to the building divided by solar irradiation is defined as the system heating efficiency.

$$\eta = c \rho q_v \Delta T / (3.6 GA_c) \qquad (eq. 1.1)$$

Where

c: Specific heat capacity of air [J/kg/K].

 ρ : Density of air [kg/m3].

q_v: Total circulating flow [m3/h].

 ΔT : Raised temperature [°C]. $\Delta T = (T_{out}-T_a)$. T_{out} is outlet temperature, and T_a is ambient temperature.

G: Solar irradiation [W/m²].

A_c: System aperture area [m²].

Three systems are simultaneously measured and separately calculated. The air volume is steadily kept at 73 m^3/h , based on the supplier's panel parameter. The average system efficiency can be found in Table 2.

Project	System 1	System 2	System 3
Average temperature rise (°C)	16.44	17.44	16.88
Average irradiation W/m ²	728.46	728.46	728.46
Air density (kg/m^3)	1.14	1.136	1.14
Specific heat capacity (J/kg/K)	1000	1000	1000
Air volume per square meter (m ³ /h)	73	73	73
Energy output (W/m ²)	380.07	401.77	390.61
Average system efficiency	52.2%	55.2%	53.6%

Tab. 2: Efficiency comparison of three different Systems

4. System heating performance

To test the heating effect of the solar air system, a small system is built whose panel has solar absorption selective coating on the front side and emittance coating on the back side, which has a better performance based on the above testing.



Fig. 6: Space heating system

The room covers an area of 8.5 m², and the heat load of the room in the heating season is 200 W/m² (based on previous test data). The aperture area of the panel is about 3 m². To test the heating effect, the solar air system is designed in the form of internal circulation, and a transparent polycarbonate cover is installed on the solar absorption panel, which can reduce the system's heat loss.

A typical day is selected in the heating season. Ambient temperature, the interlayer temperature, the room temperature, and the solar radiation on the south facade are all recorded.



Fig. 7: Performance of solar air heating system

It can be found that the solar air heating system can significantly increase the temperature in the room during cold winter. On a sunny day, it can directly replace other energy sources to heat the building. The system also can provide energy on low solar radiation days, which will reduce the building heating load and energy consumption.

5. Preliminary conclusions and next steps

The emission coating on the backside of the solar panel can significantly improve efficiency. Meanwhile, the coating can improve the anti-corrosion performance of the panel and extend the system's service life. Using selective solar absorption coating on the front of the solar panel helps to improve the solar heating efficiency of the system. However, there are some problems such as complex processing technology, poor weather resistance, and high cost, which should be further studied.

More pilot projects of this solar fresh air system should be built to conduct a more comprehensive study on the solar heating efficiency of the system, the economy of actual use, and the improvement of indoor air quality to get better guidance on the development and utilization of this solar fresh air system.

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Temperature Based Determination of Volume Flow Rates in Pipes as a Low-Cost Option for Energy Measurements of Solar Thermal Systems

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Abstract

The aim of the scientific investigations presented here is the development of a new method for cost effective determination of volume flow rates in pipes, which can be used for energy measurement of solar thermal systems. The main advantage of this approach is that relatively expensive measurement technology for determining volume flows can be dispensed with. This newly developed method analyses the course of temperature propagation delay between two temperature profiles, when volume flow occurs in the hydraulic loop considered. This is a chieved by installing a measurement track with two temperature sensors placed at a known distance a part in the hydraulic loops associated with the thermal system. Once the volume flow in each loop of the solar thermal system (i.e. solar collector loop, a uxiliary loop, heating loop, domestic tap water) is determined by analyzing the temperature profiles recorded at the temperature sensors in the measurement track, the heat associated with the corresponding loop could also be determined. When it comes to small solar thermal systems, conventional heat meters are expensive, especially considering the total cost of the thermal plant. The new measurement method is very cheap, robust and achieves an accuracy of approx. ±10 % compared to the high-end measurement equipment. Hence, it can be easily integrated into the hydraulic loops of the thermal systems and now, failures and yield reductions can be detected. Thus, it is e.g. also possible to determine the useful solar heat supplied to the domestic hot water systems. This can create the prerequisite for yield-oriented promotion, especially for relatively small solar thermal systems.

Keywords: volume flow determination, solar thermal systems, energy measurement, heat meter

1. Introduction

Currently the energy balancing of solar thermal systems is carried out by installing heat meters in to each hydraulic loop of the thermal system. Installation of the heat meters are expensive compared to the total cost of the solar thermal system. Hence contribution of the solar energy in to small thermal systems are often neglected. Heat meters are expensive as they use expensive flow sensors to determine volume flow rate in pipes. This scientific work illustrates the development of a new cost-effective method to determine the volume flow rate within a pipe by analyzing the course of temperature propagation delay between two temperature sensors placed in the pipe at a known distance apart. Different algorithms are developed in the course of the project TeBwA (Temperature-based energetic balancing of thermo-technical systems) to determine the time propagation delay between the temperature profiles obtained by the two temperature sensors. For the development of the method, the temperature profiles were generated in a test rig especially designed to generate the temperature profiles characteristics of solar loop, domestic hot water loop, heating loop, and auxiliary loop. The test rig consists of a hydraulic pump capable to generate volume flow rates in the range of 60 to 1200 l/h, and an auxiliary heater to generate temperature profiles similar to the actual thermal cycles of a solar thermal system. The auxiliary heater is also needed and to be actuated in the hydraulic loops whenever natural temperature dynamics is not sufficient enough to be analyzed by the algorithms when fluid flows through the pipes.

A newly developed measurement track is also installed in the hydraulic loops of four solar thermal systems and data from these real systems are also evaluated using the algorithms developed. In addition to experimental data from the test rig and real data, synthetically generated data for different hydraulic loops of solar thermal systems simulations with TRNSYS18 (Klein 2017) are also used to evaluate the algorithms developed. This paper presents the newly developed algorithms and its results to the temperature-based determination of volume flow rates in pipes.

2. Methodology

In order to a chieve the objective of determining the volume flow in the pipes based on temperature measurements only, a measurement track was designed and build as shown in Fig.1 with a length of 480 mm and an inner diameter of 16 mm. If the volume flow rate in the hydraulic loop is very high for example above 1200 l/h the length of the measurement track is increased up to 1900 mm. This is because, when flow velocity is high a lead time is needed for obtaining identifiable temperature profiles at the second temperature sensor. High-volume flow rates will be usually observed in the auxiliary heating loop (pellet boiler, gas boiler) and domestic hot water loops of the solar thermal system. This length adjustable measurement track will be integrated to the actual hydraulic loops of the thermal system.



Fig. 1: Measurement track with temperature sensors

When water flows through the measurement track from sensor 1 to sensor 2 (shown in blue arrows) during operation of the test rig or the actual hydraulic loop, the temperature of the water is measured at two points with temperature sensors. The profiles of two temperatures measured with a resolution of 10 values per second can be seen in Fig. 1, which were inserted against the direction of flow in order to ensure optimum measurement quality of the respective temperatures of the flowing water. In order to ensure the temperature is distributed as homogeneously as possible across the cross-section of the pipe, swirlers were also inserted into the pipe immediately before the temperature sensors. The values of temperatures will be recorded continuously by the measurement system.



Fig. 2: Example of a temperature profile obtained by the measurement track

Fig. 2 shows an example of temperature profiles recorded at the two temperature sensors of the measurement track. It is obvious that the second temperature profile is lagging behind the first temperature profile by kt_{lag} index positions. Index positions are the time of order of recording temperature values by the two temperature

sensors. When volume flow is present, by analyzing two temperature profiles the propagation delay 'k t_{lag} ' is find out using the algorithms developed as the second temperature profile is the replica of the first temperature profile with a time shift 'k t_{lag} '. Considering 'A' is the area of cross section of pipe and 'L' is the distance between the two temperature sensors installed, the volume flow rate 'V's given by equation 1,

$$\dot{\mathbf{V}} = \frac{A \cdot L}{\mathrm{k}t_{lag}}$$
 (eq. 1

using this principle volume flow is determined in the hydraulic loops of the thermal system. The above described measurement track will be implemented to each hydraulic loop of the solar thermal system as shown in Fig. 3.



Fig. 3: Measurement track with temperature sensors (TeBwA module) installed in the hydraulic loops of the thermal system

To calculate the k_{lag} between the temperature profile received at the measurement track of each hydraulic loop intelligent algorithms were developed, which is described in detail in the following section. To compare the results of the new method a heat meter is also attached to each hydraulic loops of the system. When the temperature dynamics in the hydraulic loop is not sufficient enough to determine the volume flow rate by using the algorithms developed, an auxiliary electric heater is also implemented and actuated in each hydraulic loop. Once volume flow rate occurring in each loop is find out the energy associated with the volume flow also be calculated. Thus, energy entering and leaving the thermal system is calculated which leads to complete energy balancing of the heat storage.

3. Algorithms developed

In the following the most promising a lgorithms for determining the time propagation delay 'k t_{lag} ' between two temperature profiles with their results under investigation are described.

3.1 Euclidian distance method

This method works on the principle of finding the Euclidian distance (shortest length between two points) between the selected temperature points of the temperature profiles on two temperature sensors. A defined sector of the temperature curve (Ti^{in}) from the first temperature sensor is being considered by selecting $\pm m$ (number of elements chosen to define the sector) measured values from a chosen point in time, about which flow rate is to be determined as demonstrated in Frank 2001. The sector is shifted by time shift (t_{lag}) positions a cross the second temperature curve (Ti^{out}) . For each of these offsets, the mathematical distance k (t_{lag}) is calculated represented by the following equation 2

$$k(t_{lag}) = \frac{1}{\sqrt{2m+1}} \sqrt{\sum_{i=-m}^{+m} (T_i^{in}(t-t_{lag}) - T_i^{out}(t))^2}$$
(eq. 2)

The factor $(2m+1)^{-0.5}$ is a normalizing factor for k, which depends on the size of the number of elements chosen to define the sector $(\pm m)$. The time shift (t_{lag}) will be equivalent to the occurrence of an index position of minimum value of k (t_{lag}) . This 'k t_{lag} ' is used to determine the fluid running time in the pipe.

3.2 Neighborhood approach

This method aims at comparing sequences of five measured temperature values each, which are recorded by the two temperature sensors of the measuring section.





For this purpose, first a measured value from temperature sensor 1 is randomly selected, see small blue square in Fig. 4. Then, all recorded temperature values of sensor 2 are searched for which lie within a certain tolerance range to the selected measured value of sensor 1. These readings from sensor 2 represent the points that can potentially be assigned to the value originally selected at sensor 1. In order to find out which of these potentially eligible values are actually the corresponding to the measured values of sensor 1, a more detailed analysis is then performed for these points. For this purpose, for each considered measured value additionally the two temporally preceding and the two temporally following measured values are consulted. This results in sequences of five measured values of the sequences are then compared. A pairwise comparison of the upstream and downstream measured values of the sequences compared with each other is performed. This means that the first point considered in the sequence recorded by temperature sensor 1 is compared with the first point of the sequence belonging to temperature sensor 2. The same is done for the other four readings of the sequences. The aim of this comparison is to identify those two sequences of temperature values from the two temperature sensors whose temperature values have the highest possible agreement. To implement this, each sequence of measured values from sensor 1 is compared in succession with several successive sequences belonging to sensor 2.

A tolerance range is defined in which the temperature values of the respective sequences compared with each other must lie. If the differences of the compared pairs of temperature values lie within the tolerance range, then the two sequences are considered to belong to each other. In this comparison, the tolerance range is initially defined very narrowly and then gradually increased. The increase of the tolerance range is continued until a

sequence of measured values at sensor 2 could be identified whose measured values each have a distance to the corresponding measured values of the respective sequence of sensor 1 that is within the defined tolerance. Should several sequences of sensor 2 be identified at the same time, whose measured values are within the defined tolerance range of the values of the sequence of sensor 1, the sum of the differences of the pairs of the measured values of the respective sequences to be compared with each other is calculated. The sequence of sensor 2 with the lowest value is assigned to the respective sequence of sensor 1. This results in five measured values at sensor 2 that lie within this tolerance range and thus represent the points in question. For these five measured values, a more detailed analysis is then carried out on the basis of the two temporally upstream and downstream measured values from sensor 1, the temporal distance of these sequences is calculated. For this purpose, the index positions of the measured values are used. The index position of the third measured value of the sequence of sensor 1 is subtracted from the index position of the third measured value of the sequence of sensor 2. Since all measurements are carried out with a temporal resolution of ten measured values per second, the result of the subtraction is in the un it [0.1s].

3.3 Slope method

The Slope method is a statistical approach where the physical phenomenon of water flowing through the pipe is identified in terms of numbers. The statistical quantity determined by this method is used to determine the volume flow rate. When flow takes place, the statistical quantity obtained by this method describes the time delay between two temperature sensors. The average increase or the average decrease of the temperature of a certain number of measured values of sensor 1 is used. Accordingly, the average change in temperature over a certain period of time is used to calculate the volume flow. The mentioned time period is first estimated from the expected level of the volume flow to be calculated. This rough estimate is necessary to ensure that the fluid particles of the flow have sufficient time to travel from temperature sensor 1 to temperature sensor 2 within the time period considered. The amount of flow was assumed to be between 1701/h and 12001/h and therefore 2.1 seconds was set as the maximum time period. The measurement technology implemented records ten measured values per second. This means that 21 temperature values of each sensor are used for the calculation during the period under consideration. These 21 values of each sensor are initially each stored in a field or array.

$$X_{1} = \begin{bmatrix} T_{1,1}; T_{1,2}; T_{1,3}; ...; T_{1,21} \end{bmatrix}$$
(eq.3)
$$X_{2} = \begin{bmatrix} T_{2,1}; T_{2,2}; T_{2,3}; ...; T_{2,21} \end{bmatrix}$$
(eq. 4)

Subsequently, the a verage temperature T_c is calculated from the 21 temperature values of the array X_1 belonging to sensor 1

$$T_c = \frac{\sum_{n=1}^{21} T_{1,n}}{21}$$
 (eq. 5)

Then, from the temperature values stored in array X_1 , that value T_0 is determined which has the smallest deviation from T_c , so that applies:

$$T_c \approx T_0$$
 (eq. 6)

Next, the slope S is calculated according to the following formula:

$$S = \frac{T_0 - T_{1,1}}{i_0 - i_{1,1}}$$
(eq. 7)

Here, i_0 and $i_{1,1}$ stand for the index positions of the corresponding temperatures in array X_1 of sensor 1. Based on the gradient, the time delay kt_{lag} is calculated which the flow needs to cover the distance between the two sensors. For this purpose, the temperature difference of the first two temperature values of the arrays X_1 and X_2 is divided

by the previously calculated temperature gradient S. Since the distance between the temperature sensors and the cross-sectional area of the pipe through which the flow passes are known, the volume flow can then be determined.

$$kt_{lag} = \frac{T_{1,1} - T_{2,1}}{S}$$
 (eq. 8)

After the volume flow has been calculated, the arrays X_1 and X_2 are filled with new temperature values according to the following method: The index positions of the temperature values increase by one value. This removes the first temperature value of the array and replaces it with a new value, which is placed at the last position of the respective array. Afterwards, all calculation steps are repeated.

3.4 Cosine method

In this approach the evaluation algorithms are developed based on the cosine similarity of two temperature profiles. Let ' ϕ ' be the angle between the two temperature vectors, 'a' is the first temperature sensor vector anay, 'b' is the second temperature sensor vector array and 'n' is the number of data points, The cosine similarity is given by equation 9,

$$\cos(\varphi) = \frac{\sum_{i=1}^{n} a_i b_i}{\sqrt{\sum_{i=1}^{n} (a_i)^2} \sqrt{\sum_{i=1}^{n} (b_i)^2}}$$
(eq. 9)

4. Results and Discussion

The newly developed algorithms were applied to both synthetic and real data to calculate the volume flow rate using two temperature profiles obtained at the two temperature sensors. Synthetic temperature profiles of a pipe flow were generated using TRNSYS 18 simulation program. The actual data is obtained from test rig and implementing the TeBwA technology in to actual hydraulic loops of the solar thermal system. The following section explains the results obtained by the algorithms on different types of data.

4.1 Evaluation of algorithms Synthetic data

The TRNSYS 18 program was used to generate theraw data of a pipe flow. At first, water flowing through a pipe between two temperature sensors is simulated. The diameter of the pipe is 16mm, the distance between these temperature sensors was set to 5 m during the simulation. Fig. 5 shows the temperature profiles of the two temperature sensors located in the pipe flow as well as the associated volume flow rates.



Fig. 5: Synthetically generated temperature profiles of a pipe flow using TRNSYS 18

With all approaches presented in section 3, the volume flow at 500 l/h could be calculated with high accuracy. The degree of deviation between the synthetical and calculated volume flow is primarily determined by the value of the heat transfer coefficient U specified for the pipe. If this is assumed to be $0 W/(m^2 \cdot K)$, the deviation is less than 1 %. If the U-value is $12W/(m^2 \cdot K)$, which is close to real conditions, then the deviation increases to about 3 %. In the second step, synthetically generated values were used, which originate from the simulation of a complete solar system for a day.



Fig. 6: Simulation of pipe flow in solar thermal system.

Here, the distance between collector outlet and storage inlet with a length of 10 m was considered. The diameter of the pipe in this case is again 16 mm and the heat transfer coefficient U was set to $12 W/(m^2 \cdot K)$. Fig. 6 shows the resulting temperature profiles for the collector outlet temperature (blue) and the storage inlet temperature (red) as well as the corresponding synthetical volume flow (black) and the calculated volume flow (green), which is almost identical for the three approaches.

4.2 Evaluation of algorithms on experimental data

The three approaches presented in section 3 are suitable for volume flow calculation of synthetic data in a pipe flow. Then the algorithms were applied to experimentally generated data. These were generated by means of a



test rig set up specifically for this purpose (see Fig. 7).

Fig. 7: Measurement test rig to generate actual temperature profiles as of the hydraulic loops of the thermal system

Fig. 7 shows the measurement track (1) with the two temperature sensors (2) and (3) installed. The tube of the measuring section has an inside diameter of $16 \,\mathrm{mm}$ and the distance between the two temperature sensors is 0.46 m. During operation, the measuring section is provided with thermal insulation to keep heat losses between the temperature sensors to be low. The temperature sensors are 'PT100' sensors that have been fixed in the pipe by means of a compression fitting. This type of mounting puts the tips of the thermocouples in direct contact with the flowing water, allowing temperature changes in the flow to be detected immediately. Above the measuring section, two electric heating rods (4), (5) were installed in the pipe flow. With the help of these electric heaters thermal energy can be introduced into the system. The two heating rods having different electrical power. This helps the minimum level of electrical heating power to be determined experimentally, so that the temperature profiles generated still has sufficient accuracy to be calculated by the algorithms. In the actual implementation of the measurement track only one electric heater with an electric power of 1600W. In addition, the calibrated electromagnetic flow meter (6) can be seen. The flow rates measured with this flow meter serve as a reference value for assessing the accuracy of the flow rates calculated on the basis of the evaluation algorithms. The flow is generated with the aid of the pump (7). The pump and a regulating valve can also be used to vary the volume flow rate.



Fig. 8: Continuously rising temperature profile

Fig. 8 shows continuously rising temperature profiles. The temperature at the two sensors increases approximately linearly during the measurement. In order to generate such a rising profile, the heating element was switched on continuously, i.e., for the entire time interval of 60s.



Fig. 9: Volume flow rate corresponding to the rising temperature profile

Fig. 9 shows the volume flow rate observed for the above temperature profile. The volume flow rate in the considered time interval is constant and amounts to 397 l/h. The volume flow rate is calculated for every 10s and it varies from 420 to 390 l/h. The average calculated volume flow rate for 60s by the methods are approx.413 l/h, which is about 4 % in deviation in accuracy with the measured volume flow rate. The temperature dynamics is about 0.17K/s during the calculation period.



Fig. 10: Periodic temperature profile

Fig. 10 shows the temperature profiles with periodic nature. This is achieved by alternately switching the heater on for 15 seconds and off for 10 seconds. The volume flow rate varies between 174 l/h and 286 l/h. The calculated volume rate with the algorithms also has a very close agreement with the measured volume flow rate. The temperature dynamic in the pipe flow is about 0.2 K/s in the entire sequence.



Fig. 11: Respective volume flow rate for the periodic temperature profile

4.3 Evaluation of algorithms on insitu data

The measurement track is also implemented in to actual hydraulic loops of the thermal system. For this very purpose four solar thermal systems were selected in Stuttgart, Germany including solar combi systems. Fig. 12 shows an example of a temperature profile obtained from an actual solar thermal system.



Fig. 12 Temperature profiles obtained and volume flow rate calculated for an actual solar loop

The green line shows the calculated volume flow rates by analyzing the course of temperature profiles of a solar loop. The calculated and measured volume flow rate is 550 l/h and 590 l/h respectively, which is approx. -9 % deviation in accuracy. For comparing the calculated volume flow rate by the algorithms, heat meters are installed in to each hydraulic loop of the thermal system. The flow rate measured by the heat meters serve as the reference for comparison. Volume flow rates in the actual hydraulic loops of thermal systems can be determined with a deviation in accuracy of approx. ± 10 % with the newly developed algorithms. In the real operation of thermo-

technical plants, periods occur in some hydraulic circuits in which the temperature dynamics of the flowing fluid is so low that no reliable calculation of the volume flow can be guaranteed. The evaluation algorithms developed in the TeBwA project are able to detect such periods and exclude them from the calculation. To implement this, the temperature dynamics are determined simultaneously during the calculation of the volume flow. If this is below a certain limit value in the period under consideration, no volume flow is calculated for the period in question. In a next development step, it is planned to make the algorithms more intelligent such that the auxiliary heater is able to be activated automatically for a short time, if the temperature dynamic falls below the limit value in order to ensure sufficiently high temperature dynamics.

The following table 1 summarizes the above-mentioned evaluation algorithms mentioned for determining the volume flow rates in the pipes together with characteristic values for the accuracy deviation.

Type of temperature profile	Algorithm 1: Euclidian distance method	Algorithm 2: Neighbourhood method	Algorithm 3: Slope method	Algorithm 4: Cosine method
Synthetic data for increasing decreasing temperature for water flow in pipes generated by TRNSYS simulations	±3 to ±5 %	±3 to ±5 %	±3 to ±5 %	±3 to ±5 %
Synthetic data of solar loop generated by TRNSYS simulations	< ±5 %	$<\pm 5$ %	< ±5 %	< ±5 %
Exp. data & real plant data– Continuously increasing temperature profile	$<\pm9\%$	< ±5 %	< ±5 %	$<\pm9\%$
Exp. data & real plant data- temperatures created using alternatively activating the auxiliary heater	< ±5 %	±6 to ±10 %	±6 to ±10 %	±2 to ±5 %
Exp. data & real plant data– Continuously decreasing temperature profile	$< \pm 9 \%$	$<\pm 10$ %	<±10%	$<\pm9$ %

Tab. 1: Result of different evaluation algorithm for the temperature-based determination of volume flow rates in pipe

To prove the accuracy and reliability of the newly developed algorithms, experimentally generated data and real data from solar loop, boiler loop, space heating loop and domestic hot water loop of the thermal systems were used. For the actual thermal systems, heat meters are installed in each hydraulic loop, which serve as reference for comparison.

5. Conclusion and inference

This paper presents newly developed algorithms for determining the volume flow in pipes by analyzing temperature profiles. The methods developed (Euclidian distance method, Neighborhood method, Slope method and Cosine method) are suitable for determining the volume flow rates in pipes with deviation in accuracy of approx. ± 10 %. Algorithms are evaluated using experimental data, synthetic data and real data from the hydraulic loops of solar thermal systems. Considering the actual implementation of the measurement system into the hydraulic loops further development is needed. First a spect of this development is to identify the presence of water flow in the pipe. Second aspect is related to an economically feasible actuation of the auxiliary heater in the measurement system.

In principle, the approach is a cost-effective method, since only one measurement pipe, two temperatures sensors and an auxiliary heater are required. The measurement system can be easily integrated in actual hydraulic loops of thermal systems. Once the measurement system described in this paper is integrated into actual hydraulic loops of solar thermal systems, energy transport in each hydraulic loop could be determined, especially the contribution of the solar loop. Definitely, this creates the prerequisite for yield-oriented promotion, for relatively small solar thermal systems.

Acknowledgement

The activities described in this publication are being supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) under the grand number 03ETW010 (research project TeBwA: Temperature-based energetic balancing of thermo technical systems). The authors gratefully acknowledge this support and carry the full responsibility for the content of this publication.

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Drying of Asphalt Plant Aggregates Using Concentrated Solar Energy

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Abstract

This experimental study investigates the feasibility of replacing rotatory kilns in hot mix asphalt plants with concentrating solar technology. A compound parabolic concentrator is used to focus solar irradiation onto a receiver where aggregates (silica sand in this study) are placed. The constant heat flux generated is employed to heat and dry the sand particles. Instruments such as thermocouples, pyranometers, a radiometer and a balance are employed to monitor temperature, solar irradiance, heat flux generated and humidity variations. The behavior of a 75 mm sand layer thickness is studied under several conditions of humidity and solar irradiation. Results are compared to different studies made under hot air-drying conditions. Temperature up to 70°C has been reached with a low concentration ratio technology, approximately 4 suns. Moreover, a 5 mm silica sand layer thickness has been dried in about 150 minutes.

Keywords: Hot Mix Asphalt plant; constant heat flux drying; Compound Parabolic Concentrator; silica sand; Solar heating technology.

1. Introduction

The most common material used in pavements is called Hot Mix Asphalt (HMA) which consists of a mixture of approximately 90% aggregates, 5% filler and 5% bitumen. The aggregates are heated up to a temperature between 150 and 200 °C. These temperatures are achieved in rotatory kilns, which are usually fueled with heavy fuel oil, natural gas, coal, etc. which are extremely polluting. In HMA plants rotary kilns consume around 85 kWh and cause the emission of 17.82 kg of CO_2 per metric ton of HMA produced (Peinado et al., 2011).

Decarbonization has become a key point in the current development of society and in reducing the effects of climate change. The inclusion of renewable energies is essential to meet the EU's climate change goals. For instance, Concentrating Solar Technologies (CST) are suitable for both electricity and heat generation for industrial processes. In this sense, linear Fresnel beam-down (LFBD) solar field can concentrate high irradiations on heavy receivers placed on the ground, opening a new technology path for drying and heating up of asphalt aggregates up to temperatures of 150 - 200 °C (Sánchez-González and Gómez-Hernández, 2020). To prove the feasibility of this process, a LFBD is currently under construction at Carlos III University of Madrid (UC3M) (Taramona et al., 2021a, 2021b). As a previous step in this research line, a less complex technology, such as a Compound Parabolic Concentrator (CPC) has been constructed and used at UC3M to obtain preliminary results. This study aims to experimentally test drying and heating processes of aggregates by means of a concentrated heat flux provided with the CPC.

Aggregates located in the receiving plane of the concentrator form a porous medium made up of silica sand particles, air and water. Drying a porous medium is a complicated process that involves simultaneous heat and mass transfer. Various mechanisms take place, such as conductive heat transfer due to the temperature rise, latent heat transfer necessary to generate water evaporation, vapor flow generated by differential pressure and water diffusion induced by capillary forces (Tang et al., 2018).

Several studies have analyzed mass and energy transfer on porous media with convection heats induced by hot air flows. In the study carried out by Tang et al. (2018) a theoretical model of convection drying of an unsaturated porous medium through a stream of hot air at different temperatures is analyzed. Lu et al. (2005) compared the development of a theoretical model with an experimental procedure also for drying a porous medium on a cylindrical wet bed with quartz particles. Min et al. (2019) investigated the aggregate layer drying by means of a

stream of hot air at different temperatures in a 4 mm layer thickness. This last study has been used as guidance for this work.

The present study consists of analyzing the effect of concentrated irradiance over a layer of aggregates (silica sand in this work) located in the focus of a CPC. To monitor the drying process, the irradiance on the receiver and the temperature rise, a high-precision balance, a radiometer and thermocouples placed in different regions of the sand layer are used, respectively. In addition, to determine the direct solar irradiation capture by the CPC, a couple of pyranometers and a shadow ring are used.

2. Experimental set up

The experimental study of the drying of aggregates using solar concentration technology is an innovative process for which there are no references. The study carried out by Min et al. (2019) analyzes the drying of silica sand by means of a stream of hot air. This material spatially arranged in a three-dimensional network forms quartz, the main component of common aggregates used in the construction sector or in industrial processes such as those carried out by HMA plants.

Silica sand has been used because of its chemical composition similarity with the aggregates used in the asphalt industry. However, since the size of the particles is not comparable with those used in asphalt plants, silica sand particles used in this work have been characterized.

Homogeneous particles are those whose shape, size and composition are practically identical; however, this is rarely the case. Therefore, through real sizes, a representative value of the set known as the equivalent or effective particle diameter is sought. Kunii and Levenspiel (1991) characterization process for intermediate size particles is followed to calculate this parameter. Sifting experiments are done and size particle distribution is obtained. Finally calculating mean particle diameter and making use of particle sphericity, effective particle diameter is obtained. Physical properties of used particles are collected in Tab. 1.

Parameter	Value
Effective particle diameter, d_{eff} (µm)	178.15
Particle sphericity, ϕ_s (-)	0.7-0.9
Specific heat, C (J kg ⁻¹ K ⁻¹)	750.4
Density, ρ (Kg m ⁻³)	2660
Thermal conductivity, k (Wm ⁻¹ K ⁻¹)	1.4

Tab. 1: Silica sand used physical properties.

The heat flux needed to heat and dry aggregates is generated using the CPC prototype presented in Fig. 1. It redirects the incident solar rays from the lateral parabolas to the central flat area, where the receiver with the aggregates is located. It consists of a base structure made of aluminum profiles and four colorless methacrylate ribs to support and shape the lateral parabolas. Each parabola has been built using two 0.5 mm thick aluminum sheets adhered together. One for structural purposes and the other with a high reflectivity (0.85-0.95) surface to concentrate solar radiation.



Fig. 1: (a) CPC prototype (b) CPC dimensions in mm.

The lateral parabolas are designed to redirect captured rays towards two focal lines causing a heterogeneous transversal distribution of irradiance concentration over the receiver plane where the top of the aggregates' receiver is placed. It can be seen in Fig. 2 where two brighter lines appear centered in the receiving plane over aggregates showing higher irradiation concentrations. Despite heterogeneous transversal distribution, longitudinal distribution can be assumed homogeneous. This will be considered to choose the thermocouples final positions.



Fig. 2: Qualitative irradiance distribution on the receiver's surface: (a) ray tracing simulation, (b) experimental proceeding.

CPCs can harness both direct solar radiation and part of the diffuse radiation. The concentration capacity of this type of technology is defined by the geometric relationship between the area of the upper opening zone of the parabolas and the receiver plane area. The prototype used in these experimental proceedings has a 4.6 theoretical concentration ratio with an acceptance half-angle of 12.56 °. Maximum irradiances in the receiving plane will theoretically be 4.6 times the solar irradiance captured by the device.

$$C_i = \frac{A_{Aperture}}{A_{Receiver}} = 4,6 \ suns \qquad (eq. 1)$$

The CPC is used to heat and dry aggregates. These must be placed in the receiver plane. Given the solar device dimensions and the need to place thermocouples to monitor the temperature evolution of the silica sand, a rectangular receiver has been designed and built meeting the desired specifications.

Some of the specifications considered to design the receiver are same width as CPC's receiver plane, sufficient height to study different sand layer thicknesses, full receiver total weight must be under maximum balance capacity, different thermocouples positions, high temperature resistant material and prevention of particle leakage.

Finally, in Fig. 3 the designed receiver is shown. It was optimized to feature a rectangular shape 150 mm wide, 200 mm long and 162 mm high. It is made up of two side plates, two front plates and a rectangular base made of 3 mm thick aluminum sheets.



Fig. 3: Aggregates' receiver a) Design dimensions in mm, b) Real constructed design.

After preliminary tests it was found that one of the requirements was not met. There was particle leakage, so a small cell size metal mesh had to be introduced to meet all specifications described above.

Also, it was decided to set a fixed position for the base sheet. A thick sand layer would allow to know different silica sand layers behavior against the incident irradiance in the receiving plane at different exposure time. Furthermore, thermocouples positions were also fixed to determine heat diffusion inside the receiver depending on irradiance impinging on the receiver's surface. Final positions are shown in Fig. 4. Their coordinates are collected in Tab. 2.



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Thermocouple	Х	Y	Z
	(mm)	(mm)	(mm)
TC1	100	75	5
TC2	100	75	20
TC3	100	75	32.3
TC4	100	75	57.3
TC5	100	35	5
TC6	100	35	20
TC7	100	35	32.3
TC8	100	35	57.3
TC9	150	10	5
TC10	150	10	20
TC11	150	10	32.3
TC12	150	10	57.3
TC13	100	75	75

Tab. 2: Thermocouples' final coordinates.

Fig. 4: Thermocouples' final positions.

Instruments used to measure the variables of interest are two pyranometers, a radiometer, a high precision balance and thermocouples. The Hukseflux SR05-D1A3 and the Hukseflux SR15-D2A2 pyranometers measure respectively total and diffuse irradiance on the horizontal plane, while tests are taking place. The direct horizontal irradiance (DHI) on the ground is assessed by subtracting diffuse irradiance from total irradiance. Irradiance obtained with pyranometers have been compared daily with data provided by Aemet (http://www.aemet.es/es/eltiempo/observacion/radiacion/radiacion?l=madrid).

The concentrated irradiance over the receiver's plane is measured with a radiometer. It is placed in an aluminum sheet located in the center of the receiver's plane. The device used in this case is the SBG01 from Hukseflux. To monitor the mass loss due to water evaporation in drying tests the PS 10100.R2.M high precision balance from RADWAG is used. Finally, type-k thermocouples have been used to monitor the aggregates temperature evolution inside the receiver.

3. Methodology

Three kinds of experiments have been carried out: heating of aggregates without solar concentration, heating of aggregates with solar concentration and drying of aggregates by solar concentration. The difference between heating and drying tests is the aggregates' humidity content. In heating experiments silica sand does not contain water, while in drying a mass percentage of water is given to aggregates. These experiments show differences of using concentrating solar technologies for heating and the different transfer mechanisms that take place inside the aggregates.

Experiments took place in Leganés at Carlos III University of Madrid at Higher Polytechnic School campus. The location was chosen due to its proximity to the warehouse where facilities were stored, which coordinates are N 40° 20' 2'', W 3° 45' 53''. Tests were carried out between 11 a.m. and 3 p.m. in order to obtain a low cosine effect and achieve higher irradiation concentrations.

There are two main installations that must be prepared for these experiments, pyranometer's installation and the receiver with aggregates. The first one consists of a table were pyranometers and the shadow ring are anchored, Fig. 5. This installation allows an easy calibration for these devices that should be oriented after each test following their data sheet indications. The second installation depends on the performed test. In heating and drying experiments with solar concentration the receiver must be allocated inside the CPC while in heating process without solar concentration this receiver should be placed outside the CPC.



Fig. 5. Pyranometer's installation (left) and the CPC prototype used (right).

For concentrating solar experiments, temperature variation monitoring and CPC solar tracking to ensure azimuth alignment were carried out in 5 minutes intervals. Final concentrator position is achieved by visual shadow control generated by the structure itself. For the heating tests the aggregates exposure time has been 40 minutes. For the drying process exposure time has been between 90 and 180 minutes.

4. Results

CPC technology captures direct and part of diffuse solar irradiance. In all experiments, pyranometers measurements have been obtained and DHI was assessed. On sunny days, DHI reached values between 800 and 900 W/m^2 and the diffuse irradiance was lower than 200 W/m^2 . However, on cloudy days both barely exceeded 300 W/m^2 .

Irradiance concentrated on the receiver plane is measured with the radiometer. This value determines the incident heat flux on the center of the aggregates' receiver. On sunny days, it mainly depends on the direct irradiance received reaching almost 3800 W/m² while on cloudy days the heat flux obtained is significantly lower, not exceeding 1200 W/m².

The relation between the irradiance measured with the radiometer at one arbitrary point of the receiver and the DHI shows a concentration factor of approximately 4 suns. This value is close to the estimated theoretical maximum value of 4.6. However, further analyses will be carried out to assess the concentrated irradiance distribution on the whole receiver plane.

Measured temperature shows different behaviors depending on which experiment has been performed. Heating tests without solar concentration show lower values than the ones performed with solar concentration for equal exposure time while drying tests tend to reach heating procedures temperatures after drying the sand layer.



Fig. 6: Temperature profiles in a heating test without solar concentration for all thermocouples.
In Fig. 6 temperature evolution inside aggregates is shown for a heating test without solar concentration. Temperature profiles shown are grouped by color according to the corresponding thermocouple depth. Red color corresponds to thermocouples located 5 mm below the surface, the green ones 20 mm, blue for 32.3 mm, cyan for 57.3 mm and magenta for 75 mm depth, which corresponds to the lower plate thermocouple. In addition, they have been represented with different reliefs depending on Y position. The arrangement of the thermocouples in the transverse plane of the receiver for X = 100 mm and X = 150 mm is shown in Fig. 7 a and b.



Fig. 7: Thermocouple color guide a) plane X = 100 mm, b) plane X = 150 mm.

Fig. 6 shows a temperature of the lower plate higher than the rest of the thermocouples at the beginning of the test. This is because of particle receiver is built with aluminum and it is exposed to solar irradiation without insulation, so its temperature increases. On the contrary, thermocouples introduced in the receiver have a lower temperature value because particles remain in the shade until they are introduced in the receiver to start the test.

This figure also shows how deepest thermocouples present high temperature values representing profiles similar to that obtained by the thermocouple located in the lower plate. Thermocouples represented in cyan do not show the temperature profile acquired by the particles when they are heated by solar irradiation, but they rather represent the temperature profile acquired by the particles by being in contact with the base.



Fig. 8: Upper thermocouples temperature profiles in a heating test without solar concentration.

Fig. 8 shows the temperature profiles acquired by thermocouples due to the heat flux received by solar irradiation suppressing base and deepest thermocouples positions. As can be seen, they represent ascending temperature profiles where the upper layers reach higher temperatures at shorter times, stabilizing at the end of the experiment. The maximum temperature reached in this test without solar concentration was 30.83 °C in minute 40 of measurement.

It is worth noting the TC9 thermocouple fluctuating behavior, close to the surface. Controlling the thermocouples exact position is extremely difficult. In such small aggregate layer thicknesses, it is easy for one of them to be

misaligned getting closer to the surface. This is the reason why the TC9 thermocouple exhibits higher fluctuations. This presents a greater sensitivity to wind action, which increases convection losses and therefore temperature fluctuation.



Fig. 9: Temperature profiles in a heating test with solar concentration.

Fig. 9 shows temperature profiles obtained by the thermocouples located inside the particles' receiver for a heating test using the CPC prototype. It can be observed how significantly higher temperatures are reached in comparison with those obtained without solar concentration technology. Maximum temperature reached is 75.70 °C in minute 40 by the TC1.

It should be noted that for each depth (Z), thermocouples located at greater Y, that is, in the central zone (Y = 75 mm), final temperature reached is higher than that obtained by thermocouples located at the same depth for lower Y values. Moreover, it can be seen inversely how lower Y values reach more rapidly a stabilization temperature. This effect demonstrates the dependence of stabilization and maximum temperature reached on incident irradiation concentration over receiver's surface.

A summary for all heating tests comparing TC1 thermocouple profiles is shown in Fig. 10. Profiles colored in blue represent aggregates heating obtained by solar concentration. Profiles shown in orange represent temperature profiles acquired by the aggregates in the absence of concentration.



Fig. 10: TC1 temperature profiles in all heating experiments performed.

This graph compares the tests carried out with concentration and without solar concentration. Despite the meteorological dependence of this type of technology (Test 5), it can be observed the utility for favorable days. Making use of simple concentration technologies, as is the case of a CPC with a low concentration factor, 4 suns, temperatures above 70 °C could be reached.

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Finally, drying experiments have been carried out. Moisture percentage present in aggregates used at asphalt industry ranges from 1-7% (Peinado et al., 2011). In these tests, different humidity percentages were analyzed to obtain different results. Mixtures with 5, 10 and 20% humidity were prepared.

Mixtures with higher water content did not show good cohesion. Water turned out to be filtered by the particles and lost by leaks in the receiver rather than by evaporation caused by irradiance concentration. 10% moisture mixtures did not present cohesion problems, but, nevertheless, they did not show remarkable results for the exposure time that took place during the tests. Finally, tests carried out with 5% humidity showed representative results.

The study carried out by Min et al. (2020) shows drying and heating temperature profiles obtained by thermocouples. Although in this study heat and mass transfer are produced by a stream of hot air, the behavior of the porous medium must be very similar. First, profiles would increase their temperature until reaching a stable value where evaporation would occur. Later, once the thickness reaches irreducible water saturation and the area can be considered dry, thermocouples increase their temperature again due to aggregates heating. Finally, temperature reached is stabilized at the air stream temperature used in each case. In the experiments carried out in this study, temperatures reached at the end of each test depend on the incident concentration flux on the receiver's surface.

In Fig. 11, the temperature profile acquired by the TC1 thermocouple shows the drying process in the initial phases described above. The initial stage of temperature increases and stabilizes due to upper layer moisture evaporation (Z = 5 mm). From minute 60 approximately, it is detected a perturbation in the slope associated with the end of evaporation process and the beginning of heating process.





Moreover, temperature in lower layers decreases its value at the beginning. Evaporation process requires large amounts of energy. In this case, it acquires it from deeper areas. The temperature reached is the wet bulb temperature. This is the one at which convection heat is offset by latent heat necessary for evaporation. The wet bulb temperature can be extracted from the psychrometric diagram where moist air properties, that in this case make up the porous medium, are exposed. The mixture introduced into the receiver is initially at a temperature of 18 °C, assuming an 80% air moisture content inside, wet bulb temperature reached is approximately 16 °C, value obtained in experimental tests.

Finally, a test that combined the previous ones was carried out, a drying and heating test. A mixture with 5% moisture water content has been exposed 180 minutes to solar irradiation concentration. Temperature profiles are shown in Fig. 12. This test also shows an initial temperature decrease for deeper thermocouples due to the energy input necessary for evaporation process. In the same way as in the previous test, if air temperature contained in aggregates at the beginning of the test is 18 °C and it is assumed that relative humidity is close to 80%, the wet bulb temperature that should be reached would be close to 16 °C, approximately the value obtained in the experiment.



Fig. 12: Temperature profiles in the drying and heating test.

In addition, the stabilization and the slope change associated with the end of water evaporation can be observed for thermocouples located in the central zone of the receiver. This change takes place around minute 70 for thermocouple TC1, 80 for TC5, 135 for TC9, and 145 for thermocouple TC2. For the first two, it is also possible to observe the temperature stabilization due to heating, reaching 70.02 °C in the case of TC1. Thus, in Fig. 13, are collected drying temperature profiles for the entire 5 mm layer of aggregates colored in red, and the drying for the central thermocouple located at 20 mm in green. Black arrows indicate the end of the drying stage and the beginning of the heating one for each profile.





In drying tests, besides the observed temperature evolution inside the receiver, it is expected to know the moisture evaporation rate. Mass loss due to water evaporation during exposure time for the drying and heating test is shown in Fig. 14. This parameter is monitored by using a high precision balance. Several disturbances were collected due to experimental proceedings so that the signal obtained has been treated by means of a moving average digital filter. To carry out a detailed study, each of the disturbances and the trend between data blocks should have to be analyzed. In this work, given the time available, it is provided an approach analyzing the set trend for each trial. There were performed three drying tests and a drying and heating test with a 5% moisture content. The evaporation mass flows obtained are collected in Tab. 3.

Drying test 5% moisture content	\dot{m}_{evap} (kg/s)	% m _{evap}
1	$2.94 \cdot 10^{-6}$	0.0038
2	$5.94 \cdot 10^{-6}$	0.0097
3	5.32.10-6	0.0068
Drying and heating test	3.10.10-6	0.0079





Fig. 14: Mass loss due to water evaporation at drying and heating test performed.

5. Conclusions

The main objective of this work was to obtain experimental results of aggregates drying by means of a concentrated heat flux. This is a fundamental and necessary step for the future integration of solar thermal technology in HMA plants. Thus, the study of heat and mass transfer mechanisms on a bed of silica sand, the main component of asphalt mixtures, has begun.

Results obtained show the effect of irradiance concentration on a porous medium. The temperatures reached within aggregates depend on the concentrated irradiance impinged on the receiver plane. It is demonstrated that for simple concentration technologies with low concentration capacities, approximately 4 suns, temperature of up to 70 °C can be reached.

In the drying tests, the evolution of temperature profiles inside aggregates has been compared with that obtained by Min et al. Short exposure times, 90 minutes, drying stages have been identified in different tests for a surface and centered area of the receiver. For long exposure times, 150 minutes, drying profiles have been obtained for the entire thickness of a 5 mm layer of silica sand.

Operating temperatures required by HMA production plants range between 150 and 200 °C. More complex solar concentration technologies, with higher concentration ratios (15-35 suns), as for example a linear-Fresnel beam down technology would allow the generation of higher heat fluxes and, therefore, provide higher temperatures. In addition, they would decrease the residence time in the receiver, which would imply a greater production of asphalt. For this purpose, a solar concentration prototype, based on the LFBD technology is currently being developed at Carlos III University of Madrid.

6. Acknowledges

The authors wish to thank the support for the research project INTECSOLARIS-CM-UC3M, funded by the call "Programa de apoyo a la realización de proyectos interdisciplinares de I+D para jóvenes investigadores de la Universidad Carlos III de Madrid 2019-2020" under the frame of the "Convenio Plurianual Comunidad de Madrid - Universidad Carlos III de Madrid".

The authors wish to thank "Comunidad de Madrid" for its support to the ACES2030-CM Project (S2018/EMT-4319) through the Program of R&D activities between research groups in Technologies 2018, co-financed by European Structural Funds.

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Feasibility study on hydrate-based carbon capture driven by solar thermal sorption chiller

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Abstract

Hydrate-based carbon capture is a promising method for carbon dioxide (CO_2) capture but consumes a large amount of energy in cooling. This paper investigates the feasibility of CO_2 capture from CO_2-N_2 mixtures driven by solar thermal sorption chillers with the addition of thermodynamic promoter tetra-*n*-butylammonium bromide (TBAB) and kinetic promoter sodium dodecyl sulphate (SDS). In the gas mixtures of CO_2-N_2 , CO_2 molar fraction varied from 32.3 to 76.0 mol%, which covered a wide range of flue gas compositions. CO_2 gas uptake, CO_2 split fraction and separation factor at temperatures up to 285.45 K and 4.5-MPa feed pressure are studied. The temperature ranges are designed based on the chilled water temperature of an adsorption chiller in Shanghai. The effects of CO_2 fraction in the feed gas and TBAB concentrations on the CO_2 recovery performance are discussed. In addition, the binary effect of TBAB and SDS is disclosed. The results show that the chilled water temperature from solar thermal driven chillers is sufficiently low to trigger CO_2 hydrate formation thermodynamically, and the kinetic performance can be improved by SDS. The combination of TBAB and SDS has the best separation performance under study.

Keywords: Carbon capture, CO₂ hydrate, Tetra-n-butylammonium bromide, Sodium dodecyl sulphate, Separation factor.

1. Introduction

Carbon capture and storage (CCS) technologies have been recognized as one of the most effective ways to reduce CO_2 emission and mitigate the greenhouse effect (Sun and Zhang, 2016; Zhang et al., 2018). The conventional CO_2 capture technologies include chemical absorption, physical adsorption and membrane separation (Park et al., 2017). Although these technologies have been commercially available for over 50 years, it is shown that such technologies increase the power plant energy requirement by 25–40% (Haszeldine, 2009; Mondal et al., 2012), and may generate a corresponding negative impact on the environment due to the solvent emission (Chazallon and Pirim, 2018). Currently, hydrate-based carbon capture (HBCC) are getting more significant attention as a potential CO_2 capture and storage technology (Wang et al., 2020b; Zhang et al., 2021). Gas hydrates are ice-like solid compounds formed when "guest" molecules of suitable size and shape are incorporated into the well-defined cages in the "host" lattice made up of hydrogen-bonded water molecules (Park et al., 2013). Because each individual gas has different hydrate formation conditions, for example, CO_2 forms hydrate in 1.2 MPa at 273 K and H_2 hydrate in 200 MPa at 273 K, HBCC technology can separate CO_2 from mixture gases by controlling the pressure of hydrate formation.

However, the application of this new technology is limited. A key reason is the large energy consumption when cooling the materials for gas hydrate formation. Due to the high latent heat of CO_2 hydrates, the cooling capacity required in the formation is up to 507 kJ/kg (Wang et al., 2020a). A good replacement for the conventional electric cooling system is the solar thermal cooling method. The schematic of the configuration of a solar thermal sorption chiller driven hydrate-based carbon capture system is illustrated in Fig. 1. As reported in a previous publication (Zhai et al., 2014), under the weather conditions of Shanghai, the temperature of the chilled water from a 10-kW solar adsorption chiller was in a range from 283 to 288 K at 12:30–15:30 of the day, with an average of 285.3 K. According to CO_2 hydrate phase equilibrium data, this temperature cannot trigger hydrate formation at below 4.5 MPa. However, higher pressure in cooling systems may result in safety issues and high cost. In order to enable CO_2 hydrate formation at reasonable low pressure at temperatures suitable to solar adsorption cooling, thermodynamic promoters can be employed. A large body of literature has discussed the addition of thermodynamic and kinetic promoters to accelerate the rate of hydrate formation (Chen et al., 2017; Kumar et al.,

2013). Thermodynamic promoters are small molecules that take part in the hydrate cages formation together with gas molecules. The most investigated thermodynamic promoters include tetrahydrofuran (THF), cyclopentane (CP), propane (C₃H₈) and tetra-n-butyl ammonium bromide (TBAB), among which THF, CP and C₃H₈ form hydrate crystals without changing the structure of the water cavity (Dashti et al., 2015), while TBAB takes part in the process through the formation of a semi-clathrate structure by breaking the water cage (Eslamimanesh et al., 2012; Wang and Dennis, 2016). With the addition of thermodynamic promoters, the phase equilibrium temperature of hydrate formation can be raised under a certain pressure (Ma et al., 2016). Kinetic promoters increase the rate of gas hydrate formation without taking part in the gas hydrate formation itself. Commonly used surfactants, as kinetic promoters in gas hydrate forming systems, include sodium dodecyl sulphate (SDS), Tween-80 (T-80) and dodecyl-trimethyl-ammonium chloride (DTAC) (Li et al., 2010). In recent years, the effects of CO₂ capture from mixture gases in the presence of promoters have been widely studied; however, few of them focused on the binary effect of two types of promoters, and most of them only investigated gas mixtures with CO₂ molar fraction of 17–20% (Adeyemo et al., 2010; Yang et al., 2017).



Fig. 1: Schematic of a solar thermal sorption chiller driven hydrate-based carbon capture system

In this work, low-CO₂ fraction, medium-CO₂ fraction and high-CO₂ fraction CO_2 -N₂ gas mixtures are studied. TBAB and SDS are chosen as the thermodynamic and kinetic promoters, respectively. The effects of feed CO₂ molar fraction, TBAB concentration, and the combined effect of TBAB and SDS are studied. CO₂ uptake, pressure drop, split fraction and separation factor are used as performance metrics to evaluate the performance and feasibility of CO₂ capture based on hydrate formation chilled by solar absorption chillers.

2. Experimental section

2.1 Apparatus and materials

The apparatus mainly consisted of a 635-mL steel cylindrical reactor (CR, maximum pressure 30 MPa) with a mechanical stirrer on the top cover, a low-temperature thermostatic bath, a water tank, a vacuum pump, as well as a data acquisition system, shown in Fig. 2. The gas analyzer used in this study was QMS 100 Series Gas Analyser from Stanford Research Systems to measure the gas components. The pressure and temperature change inside the reactor were recorded by a pressure transmitter and a digital temperature sensor with the accuracy of ± 0.01 MPa and $\pm 0.1^{\circ}$ C, respectively.

The gases were supplied by BOC Limited, Australia. The dry molar (%) gas fraction of the binary gases was determined by gas analyzer as follows: CO_2 (76.0%)– N_2 (24.0%), CO_2 (54.1%)– N_2 (45.9%), CO_2 (32.3%)– N_2 (67.7%), corresponding to the high-fraction, medium-fraction and low-fraction CO_2 gas mixtures. TBAB and SDS were supplied by Sigma-Aldrich with 99% purity. Deionized water was used to prepare the TBAB and SDS solution. More details of apparatus and materials are shown in Tab. 1.



Fig: 2. Experimental apparatus for gas uptake measurements.

2.2 Experimental procedures

The CO₂ capture experiments were conducted under the condition of constant temperature and volume. The CR was first washed and rinsed with deionized water for at least three times. The amount of TBAB or SDS solution used in each experiment was 100 mL. After the solution was charged into the CR, the reactor was sealed tightly and evacuated by a vacuum pump to ensure no air in CR. Then the reactor was cooled by the thermostatic bath. When the CR was cooled and remained stabled at the desired temperature, the CR was pressured by CO₂–N₂ mixture gases to 4.5 MPa in this study. At this point, the data acquisition system started to record the pressure and temperature of CR every 10 seconds. As soon as the formed hydrate crystals were observed through the visual windows, the remaining gas composition in the CR was detected by the gas analyzer every 30 minutes. The effect of gas loss on the system by using the gas analyzer, normally 0.3–0.5 mL, was ignored. The QMS series gas analyzer had a fast response time of less than 0.5 seconds. Each experiment was run for 4 hours after crystal formation to compare the amount of CO₂ captured. The constant temperature is maintained at the desired value shown in Tab. 2 to emulate different chilled water temperatures from a solar thermal driven chiller. These temperature sets can also prevent the formation of TBAB hydrate in the absence of gas, based on the concentration of TBAB solutions (Oyama et al., 2005).

Tab. 1: Apparatus and	l materials properties
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Apparatus/materials	Model	Technical index	Supplier
Cylindrical reactor	316L steel	635 mL, 30 MPa	Hai'an Scientific Research Apparatus Co., Ltd, China
Speed motor	MY- 358	200 W	Hai'an Scientific Research Apparatus Co., Ltd, China
Thermostatic bath	HX- 1030	From −10 to 99.99 °C, 30 L, 16 L/min	TOPTION Group Co., Ltd, China
Vacuum pump	2XZ-2	-0.1 MPa	Hai'an Scientific Research Apparatus Co., Ltd, China
Pressure transmitter	PS2-8	$40 \text{ MPa} \pm 0.01 \text{ MPa}$	Hongrun Research Co., Ltd, China
Temperature sensor	KS390	From –20 to 100° C, $\pm 0.1^{\circ}$ C	Yudian Electronic Co., Ltd, China
CO_2	_	Purity 99.99%	BOC Limited, Australia
N_2	_	Purity 99.99%	BOC Limited, Australia
TBAB	_	Purity 99%	Sigma-Aldrich, Australia
SDS	_	Purity 99%	Sigma-Aldrich, Australia

2.3 Performance metrics

The performance of studied recipes was quantified and evaluated based on different parameters. The pressure drop and CO_2 uptake were calculated for each experiment. According to Linga et al. (Linga et al., 2007), two metrics, split fraction (S.Fr.) and separation factor (S.F.) were calculated by the following equations.

CO2 recovery or split fraction (S.Fr.)

S.Fr. =
$$\frac{n_{\rm CO_2}^{\rm H}}{n_{\rm CO_2,0}}$$
 (eq. 1)

where $n_{CO_2,0}$ is defined as the number of moles of CO₂ in feed gas and $n_{CO_2}^{H}$ is the number of moles of CO₂ in hydrate phase at the end of the experiment.

Separation factor (S.F.)

S.F. =
$$\frac{n_{CO_2}^H \cdot n_{N_2}^{gas}}{n_{N_2}^H \cdot n_{CO_2}^{gas}}$$
 (eq. 2)

where n_X^{gas} is the number of moles of X in the gas phase at the end of the experiment, and n_X^{H} is the number of moles of X in the hydrate phase.

Exp. No.	Gas composition	Solutions	P _{exp} (MPa)	$T_{exp}\left(K ight)$
1	CO ₂ (76.0)/N ₂ (24.0)	TBAB 16 wt%, 100 mL	4.50	283.15
2	CO ₂ (76.0)/N ₂ (24.0)	TBAB 32 wt%, 100 mL	4.50	285.15
3	CO ₂ (54.1%)/N ₂ (45.9%)	TBAB 32 wt%, 100 mL	4.50	285.15
4	CO ₂ (32.3%)/N ₂ (67.7%)	TBAB 32 wt%, 100 mL	4.50	285.15
5	CO ₂ (76.0)/N ₂ (24.0)	TBAB 40 wt%, 100 mL	4.50	286.65
6	CO ₂ (76.0)/N ₂ (24.0)	SDS 1000 ppm, 100 mL	4.50	276.35
7	CO ₂ (76.0)/N ₂ (24.0)	TBAB 32 wt%+ SDS 1000 ppm, 100 mL	4.50	285.15

Tab. 2: Summary of experiments conditions

3. Results and discussion

3.1 Effect of TBAB concentration on pressure drop

Fig. 3 shows a comparison of pressure drop during the experiments in three different TBAB concentrations under the same feed CO_2 molar fraction of 76.0%. The experimental temperatures were maintained at 10, 12 and 13.5°C to emulate various chilled water temperatures from a solar thermal driven chiller.



Fig. 3: Effects of TBAB concentration on pressure drop at the same feed CO₂ gas molar fraction of 76.0%.

Compared with 16-wt% and 40-wt% TBAB, 32-wt% TBAB had the highest gas uptake in this study, indicated by the largest pressure drop. Based on the phase equilibrium conditions (Ye and Zhang, 2012), 32-wt% TBAB had higher equilibrium temperature than 16-wt% TBAB and 40-wt% TBAB. TBAB takes part in the process through the formation of a semi-clathrate structure by breaking the water cage. For a polar ionic promoter such as

TBAB, it can easily result in low gas uptake due to the high mass transfer resistance caused by dense hydrate layer (Li et al., 2010). So if the concentration of TBAB is too high, it will be difficult for gas molecules to enter the hydrate cages.

3.2 Effect of TBAB and SDS on the kinetic performance

SDS is a kind of surfactant used as a kinetic promoter in hydrate formation. Kinetic promoters can speed up the rate of hydrate formation without taking part in the hydrate formation itself. To study the combined effect of TBAB and SDS, 32 wt% TBAB with 1000 ppm SDS solution were used in Exp. 7. Meanwhile, 1000 ppm SDS solution in the absence of TBAB were used as a reference. All the lines show in Fig. 4 and Fig. 5 were under the same initial CO₂ molar fraction of 76.0%. It can be found from Fig. 4 and Fig. 5 that with the addition of SDS, CO₂ uptake rate was greatly improved. Figs. 4 and 5 also show that within 4 hours, both the CO₂ uptake amount and uptake rate were the largest in SDS solution among all the experiments. This is because that SDS can enhance the mass transfer between gas phase and water phase, so that the kinetics of reaction was greatly improved in the beginning, which however kept dropping as formed hydrate blocked further gas–water mass transfer. Without SDS, TBAB in hydrate formation showed an increase at first, followed by a drop. The peaks happened after 60 min for TBAB 16 wt% and 40 wt%; and for 32 wt% it was 150 min. The average formation rates in other runs were obviously smaller than that in Exp. 6 due to the lowest experimental temperature adopted (lower by 8.75°C in average). Overall, without SDS, the formation kinetics in the presence of TBAB had a stochastic nature, although TBAB effects in formation thermodynamics are predictable. Moreover, the increase of TBAB did not increase the amount of CO₂ captured necessarily.



Fig. 6 shows the moles of CO_2 and N_2 in each experiment in the beginning and at the end of experiments. The gas uptake in solution with SDS at 1000 ppm was the highest among all the experiments, and Exp. 4 (32.3% CO_2 and 32-wt% TBAB) had the lowest gas uptake due to the lowest CO_2 proportion in the feed gas. Besides, although

pure N₂ can hardly form hydrate in such pressure, N₂ in gas mixture can form a small amount of N₂ hydrate which was, however, non-negligible. This is obvious in Exp. 4 in which the fraction of N₂ is higher than that of CO₂. In Exp. 4, the final CO₂ uptake was 0.041 moles and the final N₂ uptake was 0.038 moles. The solubility of CO₂ in water is much higher than N₂, resulting in more formed CO₂ hydrate in theory. However, the kinetic diameter of CO₂ and N₂ molecules are 0.33 nm and 0.36 nm, respectively (Cui et al., 2004), so the potential of being trapped in cages is similar. Thus, at high N₂ fractions, CO₂ hydrate cages tend to provide favorable conditions for N₂ uptake.

Fig. 7 summarised the split fraction and separation factor for each experiment. Comparing Exp. 2 and Exp. 7, it can be concluded that the combination of TBAB and SDS greatly improved the separation factor by 147.3%. The presence of SDS was helpful for the separation of CO_2 and N_2 in the solutions of TBAB. Comparing Exp. 6 and Exp. 7, the presence of TBAB, although moderated the phase equilibrium conditions and increased the separation factor, reduced the split fraction of CO_2 at the same time. Comparing Exp. 1, Exp. 2 and Exp. 5, the increment in TBAB concentration reduced CO_2 separation factor, and TBAB at 32 wt% achieved the highest CO_2 split fraction as it is the stoichiometric fraction of the hydrate. Comparing Exp. 2, Exp. 3 and Exp. 4, a drop in CO_2 mole fraction led to a lower CO_2 split fraction.



Fig. 6: Moles of CO₂ and N₂ in the beginning and at the end of experiments.



Fig. 7: Split fraction and separation factor for each experiment.

4. Summary and conclusions

In this study, CO_2 capture performance through the hydrate method from CO_2 –N₂ mixtures in the presence of tetra-n-butylammonium bromide (TBAB) and sodium dodecyl sulphate (SDS) were studied to evaluate the feasibility of solar thermal driven hydrate-based carbon capture. The CO_2 gas hydrate formation experiments were carried out in a cylindrical reactor with a certain amount of solution at a constant temperature. It was found that under the same initial pressure and TBAB concentration, the higher the CO_2 molar fraction in the feed gas mixture

the greater the split fraction. At a certain gaseous CO_2 molar fraction, 32-wt% TBAB resulted in the highest CO_2 uptake compared with 16-wt% and 40-wt% TBAB. The addition of 1000-ppm SDS sped up the hydrate formation. The combination of TBAB and SDS showed the highest separation factor among all the studied experiments. Overall, the temperature of chilled water from solar thermal driven chillers can be sufficiently low to trigger CO_2 hydrate formation thermodynamically, and the kinetic performance can be improved by SDS. Future studies is suggested to look at the performance of such systems at fluctuating chilled water temperature as most solar thermal driven chillers are periodic.

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I-01. Hybrid Heating and Cooling Systems

Experimental Study of a Heating and Cooling Pilot Installation Driven by a Hybrid PV-Thermal Solar Field

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Abstract

This paper studies the energy performance of a pilot plant of a trigeneration system, that provides heating, cooling and electricity in an office area of an industrial building, using an air-to-water heat pump, driven mainly by the electricity produced by a liquid-based photovoltaic-thermal (PVT) solar field. The heat pump has a nominal capacity of 16 kW in heating, and 10.5 kW in cooling; and the PVT solar field has a total gross area of 13.6 m², with a nominal electrical power of 2.56 kWp. The pilot installation was monitored and analyzed for eight weeks during the winter and summer seasons. The results show that under real operation conditions, the PVT solar field has average thermal efficiency between 19.3 and 22.4% during the winter weeks, and between 25.4 and 28.3% during the summer weeks. The electrical efficiency varies between 15.7 and 16.2%, with no relevant difference between the winter and summer weeks. Thanks to the PVT electrical generation and the heat pump performance,e, the system achieves high electrical solar cover factors during both: summer and winter weeks..

Keywords: Hybrid solar photovoltaic-thermal (PVT) collectors, heating and cooling, trigeneration system, energy performance, experimental performance.

Introduction

According to the latest IEA report, 32% of final energy consumed globally is concentrated in the industrial sector, 31% in the transport sector, 22% in households and 14% in other sectors (United Nations - Department of Economic and Social Affairs, 2021). The distribution by use indicates that 51% of total final energy is dedicated to thermal uses (heating and cooling), 32% to transport uses and 17% is dedicated to electricity production (REN21, 2021).

The energy intensity in the building sector has been decreasing slowly during the last two decades, especially in developed countries. However, the energy demand from buildings and building construction is rising in absolute values, due to the population growth, the better electricity access in the developing countries and the increase of space cooling demand in developed countries (IEA, 2021). In this context, the need for reduction of CO2 emissions requires the acceleration change in the energy model, including several technological lines such as the improvement of the building envelope, the use of more efficient systems for space heating and cooling, the increase of the share of renewable production in buildings as well as the implementation of smart controls in these different systems (Delmastro et al., 2021; IEA, 2021).

Solar energy technologies (thermal and photovoltaic) are options easier to implement in buildings. Until now, solar thermal technology is mainly dedicated to domestic hot water production while photovoltaic (PV) technology is focused on producing electricity for several uses in buildings. photovoltaic-thermal (PVT) technology combines in one unit both solar technologies with better overall efficiency, in comparison to separated photovoltaic and solar thermal technologies (Al-Waeli et al., 2019; Zondag, 2008). The progressive decrease of PV laminate prices since the beginning of the XXI century has improved the competitiveness of PV technology as well as the hybrid PVT technology; in fact, by 2019 there were 24 manufacturer companies of PVT technology located in the European countries (Baggenstos et al., 2019).

The use of solar energy for cooling generation is an option of great interest, since the solar resource reaches its highest values during the summer, coinciding with the peak demand for space cooling. Trigeneration systems for the production of heat, cold and electricity, driven by solar energy, usually solar thermal energy, have been analyzed and implemented within the framework of various research and development programs (Henning et al., 2013). The implemented solutions use mainly two options: thermally driven absorption/adsorption machines in combination with solar thermal technology, and electrically driven mechanical compression heat pumps in

combination with PV technologies. There is also more recent work that combines PVT technology in trigeneration systems (Calise et al., 2016; Herrando et al., 2021, 2019; Lazzarin, 2020; Ramos et al., 2017). In this case, almost all studies are focused on the experimental, simulation, and economically analysis in the early stages; however, there are still few implementations that show performance results in a real environment (Baggenstos et al., 2020).

This paper presents the performance results of a solar trigeneration system, that integrates an air-to-water reversible heat pump with a PVT solar field by using thermal storage tanks, that provide heating at low temperature, domestic hot water and cooling in the office space in an industrial building located in Zaragoza (Spain). The plant was operated from January to September 2021 under different operation modes (winter and summer). Different operating conditions were tested for both operation modes, such as various mass flow rates in the solar circuit, different temperature setpoints for heating and cooling, and different thermal storage volumes.

Several performance indicators were calculated, including the PVT solar field efficiency (electrical and thermal), the weekly and daily heat pump (HP) performance factor, the PVT solar thermal fraction, as well the HP electrical self-sufficient ratio. The paper shows the main results for 4 weeks during winter and 4 weeks during summer. These indicators show that the system achieves very high solar contribution factors (electrical and thermal), and is a feasible technical option to be applied in the net-zero building context and can contribute to the energy transition.

Methodology

2.1. Pilot installation description

The trigeneration pilot installation evaluated in this paper is used in an industrial building, located in Zaragoza (Spain). The building has domestic hot water (DHW) demand throughout the year, and heating and cooling demand during the winter and summer periods respectively. The DHW demand varies depending on the productive activity of the industry. The demand for heating and cooling services are dedicated to an office zone, that has a total area of 53 m², an occupation of 4-5 people, who normally work from Monday to Friday and some Saturdays from 8:00 a.m. to 6:00 p.m



Fig. 1: Basic scheme of the heating and cooling solar pilot plant with the main components

The pilot plant consists of a solar PVT field of 13.6 m² with a peak electrical power of 2.56 kW, a high-efficiency air-to-water HP with a capacity of 16.0 kW in heating and 10.5 kW in cooling. In total, there are two water storage tanks of 350 l and 263 l, for domestic hot water (DHW) production and a third inertia tank, of 263 l, is used in the heating/cooling distribution circuit. The heating/cooling distribution circuit uses fan coils as thermal emitters, allowing a minimum supply temperature of 40 °C in winter and 7 °C in summer. To increase the use of low-

temperature heat, DHW is supplied at 50 °C, performing periodic sanitary heat treatments at 60 °C to avoid legionellosis. Fig. 1 presents a simplified diagram of the pilot plant, built-in 2020.

The PVT solar field consists of 8 solar hybrid PVT collectors, manufactured by EndeF, arranged in two arrays (Fig 1). The PVT collectors are unglazed, with a nominal electrical power of 320 Wp each, and a sheet-and-tube heat exchanger. The gross and absorption areas of the PVT collector are 1.70 m² and 1.35 m² respectively. The reversible air-to-water HP, manufactured by Hitachi, the Yutaki S6, has a nominal capacity and coefficient of performance (COP) of 16.0 kW and 4.57 in heating mode, and 10.5 kW and 3.31 in cooling mode. The seasonal COP (SCOP) values indicated by the manufacturer are 3.90 for heating production at 55 °C, and 2.84 for cooling production.

The system is controlled by two units. The first unit is linked to the solar thermal circuit; it consists of an off-on controller that measures the temperature difference between the PVT solar field outlet and the bottom zone of the tanks; when the temperature difference is above 5°C, the solar circulation pump is activated; when this difference is below 2°C the solar pump is turned-off. The Charging process of both tanks (DHW and Inertia) is carried out alternately, giving priority to the DHW tank. During summertime, the charging process in the inertia tank is deactivated, since there is no demand for heating.

The second unit control is linked to the heat-pump. It consists of a PDI temperature controller that measures the temperatures at the top zone of the tanks. This controller maintains the setpoint temperature in each tank, and prioritizes the charging process of the DHW tank. During summertime the heat pump alternates two operation modes: heating for DHW tank and cooling for the inertia tank.

To evaluate the thermal performance of the system, 28 temperature sensors and 4 flow meters were installed in the different hydraulic circuits: solar circuit, HP circuit, hot water circuit and heating/cooling distribution circuit (see Table 1). In addition, to evaluate the electrical performance, the HP electricity consumption was measured, and the PVT electrical production was monitored through a DC/AC inverter integrated into the monitoring system. Environmental variables were also measured and monitored, including ambient temperature (T_a), incident global solar radiation (G) and wind speed (u), through which the PVT performance solar field is evaluated.

Variable	Sensor type	Amount	Specifications
Temperature	1-wire sensor Arduino	28	-55 a 125°C, +/- 0.5°C
Solar Irradiance	Thermopile pyranometer	1	0-2000 W.m ⁻² , Class 2
Wind velocity	Hemispherical cup anemometer	1	0-50 m.s ⁻¹ , +/-3%
Electrical power PVT	Sensor integrated from Inverter by Modbus	1	0-10.000 W, +/-0.001%
Electrical powe HP	Sensor integrated from HP by Modbus	1	0-40 A, +/-5%
Flow rate	Sensor volumetric sensor by pulses	4	30-3000 l.h ⁻¹ , +/- 2%
3-way valves position	Voltage sensor in datalogger	2	0 -1

Tab. 1: Summary of sensors in the monitoring system

2.2. Data analysis procedure

System operation was analysed by calculating the power and energy production from the different sources (PVT solar field, and the HP, as well as the building energy demand. Based on these calculations, different performance indicators were obtained for both operation modes: winter and summer. The general procedure applied to obtain the power production (thermal and electrical), the demand and the performance indicators are described in the following paragraphs.

• Solar irradiance and solar irradiation

Incident global solar irradiance (G), expressed in W.m-2, is measured directly from the monitoring system every 5 minutes. The incident solar irradiation (H) corresponding to the total incident solar energy H expressed in kWh.m-2, calculated for the analyzed period.

• Thermal and electrical production

The thermal and electrical productions of the PVT subsystem were calculated. Thermal production calculation considered both arrays of the PVT collectors that integrate the overall solar PVT field. The corresponding instantaneous thermal power ($q_{PVT,i}$), for the array of PVT collectors i, was obtained through equation 1, where i indicates the number of the PVT array, C_{PVT} is the specific heat capacity of the heat transfer fluid (HTF), used in the solar thermal circuit, $\dot{m}_{PVT,i}$ is the mass flow rate, and $T_{in,i}$ and T_{out} Tout, i represent the inlet and the outlet temperatures for the corresponding PVT array.

$$q_{PVT,i} = C_{PVT}.\dot{m}_{PVT,i}.\left(T_{PVT,in,i} - T_{PVT,out,i}\right)$$
(eq. 1)

Because the PVT arrays are connected hydraulically in parallel, the total thermal power produced by the PVT solar field (q_{PVT}), is obtained by adding the individual thermal productions of the different PVT arrays, according to equation 2.

$$q_{PVT} = q_{PVT,1} + q_{PVT,2}$$
 (eq. 2)

The instantaneous electrical power produced by the PVT solar field ($P_{PVT,DC}$), in Direct Current (DC), was obtained by applying equation 3, where $V_{PVT,DC}$ and $I_{PVT,DC}$ represent the DC voltage and current produced by the overall PVT solar field. In this case, the electrical power ($P_{PVT,DC}$) can be also read directly from the Inverter integrated into the monitoring system.

$$P_{PVT,DC} = V_{PVT,DC} * I_{PVT,DC}$$
(eq. 3)

Regarding the heat pump (HP), the instantaneous produced thermal power (q_{HP}) was calculated according to equation 4, where C_{HP} is the specific heat capacity of the heat transfer fluid used in the HP circuit, \dot{m}_{HP} is the mass flow rate, and $T_{HP,in}$ and $T_{HP,out}$ are the inlet and the outlet temperatures of the HP.

$$q_{HP} = C_{HP}.\,\dot{m}_{HP}.\left(T_{HP,in} - T_{HP,out}\right) \tag{eq. 4}$$

In general, qHP is positive when the operation mode of HP is heating and is negative in cooling mode. The values assigned for heating or cooling were also validated according to the operation mode of HP, which is read directly from the HP regulation unit, integrated also into the monitoring system.

The thermal production from the PVT system can be sent either to the DHW tank or to the inertia tank. To do this, the installation used the 3-way-valve 1 (3WV-1), whose position (open/closed) is monitored every minute. Similarly, the HP thermal production can be sent either to the DHW tank or to the inertia tank, by using another 3-way-valve (3WV-2), also monitored every minute.

Thermal and electrical demand

The power demand calculation includes the thermal demand for domestic hot water (DHW), heating and cooling in the building, as well as the electrical consumption for the HP.

Similarly, as before, the thermal and electrical demands were obtained from the mass flow rate and temperatures measured in the two energy demand circuits. The thermal for DHW (q_{DHW}) was obtained through equation 5, where C_W correspond to the cold-water specific heat capacity, \dot{m}_{DHW} is the mass flow rate in this circuit, and T_W and T_{DHW} indicates the inlet cold water and the outlet hot water temperatures, respectively,

$$q_{DHW} = C_W . \dot{m}_{DHW} . (T_W - T_{DHW})$$
 (eq. 5)

Likewise, for the heating/cooling distribution circuit (with fan coils (FC) emitters), the instantaneous thermal demand was calculated using equation 6, where C_{FC} is the specific heat capacity of the HTF used in this circuit, \dot{m}_{FC} is the corresponding mass flow rate, and $T_{FC,sup}$ and $T_{FC,ret}$ are the supply and return temperatures in the circuit, respectively,

$$q_{FC} = C_{FC} \cdot \dot{m}_{FC} \cdot (T_{FC,sup} - T_{FC,ret})$$
 (eq. 6)

Because one of the purposes of this trigeneration system is to cover the electrical consumption of the HP, the electrical demand of this equipment was calculated for the heating and cooling operation modes, according to equation 7, where V_{LL} is the Voltage line-line in the AC electrical grid, and I_{HP} is the three-phase AC electrical current demanded by the HP. These variables were read directly from the HP regulation unit, integrated into the

monitoring system.

$$P_{HP} = \sqrt{3} * V_{LL} * I_{HP}$$
 (eq. 7)

• Performance indicators

To evaluate the energy performance of the PVT solar field, two main indicators were considered: the PVT thermal efficiency $(\eta_{PVT,th})$ and the PVT electrical efficiency $(\eta_{PVT,el})$. The PVT thermal efficiency was calculated according to equation 8, where q_{PVT} is the thermal production of PVT solar field, calculated with equation 2, *G* is the total incident global solar irradiance, expressed in W.m⁻², and A_{PVT} is the gross area of the PVT solar field.

$$\eta_{PVT,th} = \frac{q_{PVT}}{G.A_{PVT}}$$
(eq. 8)

Similarly, the electrical efficiency $(\eta_{PVT,el})$ of the PVT solar field was calculated according to equation 9, in which the P_{PVT-DC} , corresponds to DC power production, and *G* is the total incident global solar irradiance. Daily and monthly efficiency values were also calculated taking into account the overall incident solar irradiation and thermal/electrical production throughout the day and week.

$$\eta_{PVT,el} = \frac{P_{PVT-DC}}{G.A_{PVT}}$$
(eq. 9)

Inverter efficiency, η_{INV} is calculated as the ratio between the PVT electrical production in direct current P_{PVT-AC} , and the PVT electrical efficiency in alternating current P_{PVT-DC} , according to equation 10.

$$\eta_{INV} = \frac{P_{PVT-AC}}{P_{PVT-DC}}$$
(eq. 10)

The HP coefficient of operation (*COP*_{HP}) was calculated as instant values, every 5 minutes, according to equation 11.a, where q_{HP} and P_{HP} correspond to the instantaneous thermal power production and electrical power consumption of the HP. In addition, the HP performance factor (*PF*_{HP}) was also calculated for the daily and weekly thermal energy production Q_{HP} and electrical consumption E_{HP} , according to equation 11.b,

$$COP_{HP} = {q_{HP}}/{P_{HP}}$$
 (eq. 11.a)
 $PF_{HP} = {Q_{HP}}/{E_{HP}}$ (eq. 11.b)

The solar thermal fraction of the PVT subsystem ($SF_{PVT,th}$), is calculated according to the equation 12.a, where, Q_{PVT} corresponds to the thermal production of the PVT solar field, and Q_{HP} is the thermal production of the HP. Finally, the electrical ratio PVT production - HP consumption (ER_{PC}) is calculated, as the ratio between the AC electricity production of the PVT solar field ($E_{PVT,AC}$) and the HP electricity consumption (E_{HP}), as equation 12.b indicates.

$$SF_{PVT,th} = \frac{Q_{PVT}}{Q_{PVT} + Q_{HP}}$$
 (eq. 12.a)
 $ER_{PC} = \frac{E_{PVT,AC}}{E_{HP}}$ (eq. 12.b)

Main results and discussion

3.1. Winter operation mode

Under the winter operation mode, the HP is configured to provided domestic hot water (DHW) and heating (at low temperature), and the PVT system can provide DHW, heating and electricity, whose main purpose is to cover

the HP electricity consumption.

The HP was set at 50°C for DHW preparation, instead of the typical value of 60°C, to enhance the solar thermal contribution of the PVT solar field. As it is well known, the heating circuit, that uses fan-coils as thermal emitters, usually operates in a close loop with an internal ΔT close to 5°C. In this case, the tests were performed with two values of supply/return temperature, at 45/40 °C and 40/35 °C.

The monitoring system allows to measure and follow the evolution of the temperatures and flow rates of the different circuits. Fig. 2 illustrates some data monitored during one winter week (Feb 15 to Feb 21), in which the average global incident radiation was 3.77 kWh.m-2.day⁻¹, and the ambient temperature ranged from 5 to 20°C (Fig.2.a). The thermal energy demand reached weekly values of 14.5 kWh for DHW and 155.1 kWh for heating, which implies that the heating demand represented 91% of overall thermal demand (Fig.2.b). During this week, the output temperature of the PVT solar field rarely reached values above 40°C (Fig.2.c), which limits the solar thermal contribution to the heating circuit. PVT electrical production, however, allowed to cover almost all the HP electricity consumption (Fig.2.d)



Fig. 2: Monitoring temperatures and relevant variables in the pilot plant from Feb 15 to Feb 21 in 2021

Table 2 summarizes the main results for the different weeks tested under winter operation mode, between February and March of 2021. The PVT thermal efficiency, calculated on a weekly basis has an average value of 19.2 %; and the average PVT electrical efficiency was 15.9%. The DC/AC inverter efficiency had an average weekly value of 92.1%.

As underlined before, the solar thermal fraction ($SF_{PVT,th}$) is relatively low under this operation mode, with average weekly values between 0.07 and 0.11; however, the electrical ratio PVT production - HP consumption (ER_{PC}) reached very high values, between 0.95 and 1.16, which implies a high global solar contribution factor of the PVT system to the thermal demand. The HP performance factor (PF_{HP}), ranged between 3.6 and 4.0, during the evaluated weeks, with an average value of 3.8, very close to the nominal SCOP for heating stated by the HP manufacturer (3.9). As expected, the PF had better values during the week with less severe environmental conditions (Feb 22-28).

Weeks	Units	Ι	II	III	IV
week:		Feb 8-14	Feb 15-21	Mar 1-7	Feb 22-28
Based operation conditions					
HP: Setpoint DHW temperature	[°C]	50	50	50	50
HP: Setpoint supply /return temperature	[°C]	40 /35	40 / 35	45/40	45/40
Solar system: setpoint temperature DHW tank	[°C]	50	50	50	50
Solar system: setpoint temperature inertia tank	[°C]	40	40	40	40
Mass flow rate in the PVT solar field	[l.h ⁻¹ m ⁻²]	50	30	50	30
Global incident solar irradiation (H)					
H per day per unit of area	[kWh.m ⁻²]	3.77	3.50	3.01	4.18
H per week	[kWh]	359	333	286	398
<i>H per week</i> during the operation period	[kWh]	208	142	132	200
Main performance indicators					
Thermal efficiency PVT ($\eta_{PVT,th}$)	[%]	19.5.0%	18.1%	21.2%	18.1%
Electrical efficiency PVT ($\eta_{PVT,el}$)	[%]	15.8%	15.9%	16.2%	15.7%
Inverter efficiency (η_{INV})	[%]	92.5%	92.1%	91.1%	92.9%
HP Performance factor for heating (PF_{HP-H})	[-]	3.7	3.6	3.8	4.0
Solar thermal fraction PVT (SF _{PVT, th})	[-]	0.11	0.08	0.08	0.07
Electrical ratio PVT production- HP consumption (<i>ER</i> _{PC})	[-]	1.16	0.95	0.97	0.97

Tab. 2: Main performance results during winter operation mode: DHW+heating+electricity

3.2. Summer operation mode

Under the summer operation mode, the HP was configured to provide DHW and cooling, while the PVT system produced electricity and hot water to contribute to the DHW production. The system performed under this operation mode from June to August of 2021 and the main results for four selected weeks are presented in this section.



Fig. 3: Monitoring temperatures and relevant variables in the pilot plant from June 16 to June 22 in 2021

Weekly tests were performed with and without a backup for DHW production, and under two setpoint temperatures for cooling production (15 °C and 7 °C); in this case, the corresponding supply/return temperatures in the distribution circuit were 7/12 °C and 15/20 °C respectively.

Following the same procedure applied for winter operation mode, several performance indicators were calculated to evaluate the pilot plant under summer operation mode. Table 3 presents the main results and indicators for the four selected weeks between June and July of 2021.

As expected, during summer the solar incident radiation is higher than during the winter period, with an average daily value between 5.53 and 7.52 kWh.m⁻².day⁻¹. The PVT thermal efficiency ($\eta_{PVT,th}$) had an average weekly value of 25.0%, which is higher than the average value obtained under winter operation mode (19.2%), mainly due to the higher solar irradiance and the less severe ambient conditions. Furthermore, this efficiency ($\eta_{PVT,th}$) has slightly better values when the pilot plant operates without a backup for DHW production, with average values with and without the backup of 24.3% and 25.7% respectively. The solar thermal PVT fraction (*SF*_{PVT,th}) had an average value of 0.65 when the HP was ON, and it increases up to 0.97 when the HP was OFF.

W 7 I	Units	Ι	II	III	IV
Week:		Jun 09-15	Jun 16-22	Jul 8-14	Jul 15-21
Based operation conditions					
HP: Setpoint DHW temperature	[°C]	OFF	50	50	OFF
HP: Setpoint supply /return temperature	[°C]	15/20	15/20	7/12	7/12
Solar system: setpoint temperature DHW tank	[°C]	60	60	60	60
Solar system: setpoint temperature inertia tank	[°C]	-	-	-	-
Mass flow rate in the PVT solar field	$[l.h^{-1}m^{-2}]$	30	30	30	30
Global incident solar irradiation (H)	•				
H per day per unit of area	[kWh.m ⁻²]	7.00	5.53	7.07	7.52
H per week	[kWh]	666	527	673	716
<i>H per week</i> during the operation period	[kWh]	498	354	487	615
Main performance indicators					
Thermal efficiency PVT $(\eta_{PVT,th})$	[%]	26.4	25.0	23.6	25.0
Electrical efficiency PVT $(\eta_{PVT,el})$	[%]	15.7	16.2	16.0	15.7
Inverter efficiency (η _{INV})	[%]	95.1	95.0	95.2	95.4
HP performance factor for heating (PF_{HP-H})	[-]	-	3.8	3.8	-
HP performance factor for cooling (PF_{HP-C})	[-]	-	3.7	2.7	-
Thermal solar fraction PVT ($SF_{PVT,TH}$)	[-]	0.97	0.6	0.7	0.99
Electrical ratio PVT production- HP consumption (ER_{PC})	[-]	2.8	1.9	3.2	1.5

Tab. 3: Main performance results during summer operation mode: DHW+cooling+ electricity

The PVT electrical efficiency ($\eta_{PVT,el}$) reaches an average weekly value of 15.9%, without a relevant decrease compared to the winter operation mode, despite the higher ambient temperature registered under the summer operation mode. This positive behaviour is linked to the cooling effect on the PV laminate that normally occurs in the PVT solar collectors. Furthermore, the DC-AC inverter efficiency reaches an average value of 95.2% that is higher than the value obtained during the winter operation mode (92.2%), due to the larger solar incident radiation and the electrical production during summer operation mode.

Concerning the HP performance, the performance factor obtained for heating (PF_{HP-H}) and cooling (PF_{HP-C}) are 3.8 and 2.7 respectively, which are close to the seasonal performance values indicated by the manufacturer (3.90 for DHW and 2.84 for cooling production). The electrical ratio PVT production - HP consumption (ER_{PC}) of the HP varies between 1.9 and 3.2, when the backup is activated, which means that the PVT electrical production can

cover the HP electricity consumption. Better values are obtained when the cooling demand is lower.

Conclusions

This paper studies experimentally the energy performance of a pilot plant of a trigeneration system, that provides heating, cooling and electricity in an industrial building located in Zaragoza (Spain), using a reversible air-to-water heat pump (HP), and a liquid-based PVT solar field. The HP has a nominal capacity of 10.5 kW in heating, and 16.0 kW in cooling; and the PVT solar field, has a gross area of 13.6 m², with a nominal electrical power of 2.56 kWp. The pilot plant was operated under two operation modes (winter and summer), and several performance indicators were calculated and analyzed for several weeks. This work shows the results of four representative weeks under winter operation mode, and four weeks under summer operation mode.

The PVT thermal efficiency has average weekly values of 19.2% and 25.0% under the winter and summer operation modes respectively. When the DHW backup is activated, there is a slight decrease in the PVT thermal efficiency, and also an important increase in the solar thermal fraction during the summer operation mode. The PVT electrical efficiency has an average weekly value of 15.9% under both operation modes (winter and summer); thanks to the cooling effect on the PV laminate, this efficiency does not decrease during the summer period, despite the larger solar irradiance and ambient temperatures.

The HP performance factor achieves averages values of 3.8 and 2.7 in heating and cooling respectively; which are in agreement with the seasonal COP for heating and cooling indicated by the manufacturer of the reversible HP used in the pilot plant. The electrical ratio PVT production - HP consumption (ER_{PC}) reaches high values under two operation modes, with average weekly values of 1.0 and 2.6 under the winter and summer periods, respectively, when the backup for DHW is activated.

During the winter period, the solar thermal fraction has an average value of 0.09, which is relatively low due to main reasons: the high fraction of the heating demand (above 90%), and the minimum required temperature for heating (40°C) which is rarely reached by the PVT solar field during the wintertime. However, thanks to the high HP electrical self-sufficient ratio, it was possible to cover the thermal demand with the HP driven mainly by the PVT electrical production both in the summer and winter seasons.

On the other hand, during the summer period, the solar thermal fraction reaches values between 0.60 and 0.70, when the backup is activated. In this case, the Electrical Ratio PVT production -HP consumption is above 1.0, which also suggests that overall, the thermal demand for heating and cooling can be fully covered by the pilot plant, using the (thermal and electrical) energy produced by the PVT solar field and the reversible HP.

The overall system performance shows that this kind of trigeneration system, in which an unglazed PVT solar field is used, reaches very high solar contribution factors (electrical and thermal), and is a feasible technical option to be applied in buildings to accelerate the energy transition.

Further work in the project involves detailed daily analyses of pilot plant performance to optimize the system operation, including, among other works, the validation of a simulation model of the pilot plant, the comparison with a reference system based on a heat pump powered by a PV system and a detailed analysis of the electricity production and demand curves to determine the directly self-consumed electricity.

Acknowledgements

This work was carried out in the framework of 3GSol project, funded under the Retos-Colaboración 2017 Programme, National R&D and Innovation Plan, by the Spanish Government, Ministry of Science, Innovation and Universities and co-funded by the EU (through the European Regional Development Fund (ERDF)) [grant number RTC-2017-6026-3].

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Appendix: Unix and Symbols

Nome	enclature		Subscripts	
Α	Area	m ²	FC	Fan coil
G	Solar irradiance	W m ⁻²	H	Heating
G'	Net solar irradiance	W m ⁻²	HP	Heat Pump
H	Solar irradiation	kWh m ⁻²	i	Number of PVT array
m	System mass	kg	in	Inlet
ṁ	Mass flow rate	kg s ⁻¹	INV	Inverter
Q	Thermal energy	kWh	LL	Line-Line
q	Thermal power	kW	out	Outlet
Ε	Electrical energy	kWh	PVT	Photovoltaic-Thermal
Ρ	Electrical power	kW	ret	Return
Т	Temperature	°C	sup	Supply
и	Wind speed	m.s ⁻¹	th	thermal
V	Voltage	V	W	Water, cold water
Ι	Current	А	PC	Produccion-Consumption
С	Specific heat capacity	J kg ⁻¹ K ⁻¹		
k	Thermal conductivity	W/K.m	Acronyms	
ρ	Density	kg.m ⁻³	COP	Coefficient Of Performance
η	Efficiency	-	DHW	Domestic Hot Water
			ER	Electrical Ratio
	Subscripts		HTF	Heat Transfer Fluid
а	ambient		PF	Performance Factor

AC	Alternating Current	PV	Photovoltaic
av, m	Average	PVT	Photovoltaic-Thermal
С	Cooling	SCOP	Seasonal COP
DC	Direct Current	SF	Solar fraction
el	electrical	3WV	3 Way Valve

Potential for Integration of a Renewable Combined Heating and Cooling System in Food Industries requiring Heat and Cold

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Abstract

Night radiative cooling can be combined with solar thermal collection in one single device to produce heat during the day and cold during the night. This device is called RCE (Radiant Collector and Emitter) and could be integrated in processes requiring simultaneous heating and cooling demands, such as the food industry, to save non-renewable primary energy and operating costs. In this paper the temperature levels and amounts of heat and cold of seven food industries are analyzed and compared with the combined heat and cold production of the RCE for three different climates in Spain to assess its potential of integration. Two different sizing of the RCE field are presented, one tracking the heat demand, and the other tracking the cold demand. Results show the natural gas and electricity energy and cost savings associated to the partial replacement of the natural gas boiler (for heating loads) and the efficiency improvement of the electrically-driven chiller (for cooling loads) by the RCE. The best match is found with the juice canning industry, with primary energy savings of 62% in heat track and 81% in cold track.

Keywords: renewable heating and cooling, food industry, radiative cooling, solar thermal collection, simultaneous heating and cooling, primary energy savings

1. Introduction

Radiative cooling (RC) is a relatively old technology, already studied in the 70s (Vall and Castell, 2017), which is recovering interest lately due to the advent of selective surfaces with nanomaterials (Raman et al., 2014). It takes advantage of the low "effective" temperature of the sky during the night to dissipate heat by radiation, thus producing cold. This "effective" temperature is influenced by the behaviour of the atmosphere known as "infrared window", which allows the pass of radiation at a certain wavelength (7-14 μ m). Heat dissipation is produced by longwave radiation (thermal radiation) from a surface to the sky. The sky temperature during the night allows suitable cooling as temperatures can be lower than 0°C or even -10°C (Bell et al., 1960), During the day the solar radiation (shortwave radiation) is higher and the radiation balance results in thermal gains (heating). To produce cold a high emissivity radiative surface is needed and connected to different pipes where a fluid is circulating. The radiative surface emits energy as thermal radiation to the sky, cooling down the fluid by using a cover material transparent to thermal radiation.

Furthermore, this technology can be coupled with a flat plate solar thermal collector (Vall et al., 2020), creating a new device, the Radiative Cooler and Emitter (RCE), capable of producing in a renewable way hot water and cold (to support the cooling system), reducing the non-renewable energy consumption during the whole year, as well as the maximum installed power of the conventional production systems. Nowadays solar collectors are a well stablished technology, where research focuses on the use of selective surfaces (Suman et al., 2015; Valleti et al., 2014), nano-fluids (Suman et al., 2015; Verma and Tiwari, 2015) and concentration systems (Colangelo et al., 2015), but the radiative cooling technology shows a reduced development due to the lack of suitable materials and solutions in order to reduce the heat gains and the low energy density available (between 20-80 W/m2 (Cavelius, R. et al., 2005)). The most used solar thermal collectors in Europe are the flat plate solar collectors (mostly used for domestic hot water (DHW) production).

Little research has been done in the combination of both solar collection and radiative cooling in a single device

(Erell and Etzion, 2000, 1996), but conventional covers are not suitable for radiative cooling. In this paper, a suitable adaptive cover, capable to adapt its optical properties to allow either thermal radiation to pass through (for radiative cooling) or block thermal radiation (for solar collection) is implemented in the new RCE device, as explained in (Vall et al., 2020). More recently, significant developments have been achieved in the field of materials capable to produce radiative cooling during both night and daytime. In 2013 at Stanford University, Rephaeli et al. were the first ones to develop such a material (Raman et al., 2014; Rephaeli et al., 2013). In 2015, Hu et al. (Hu et al., 2015) developed a spectral selectivity surface suitable for both solar collection and radiative cooling. The new surface, the TPET presents high absorptivity/emissivity in both the solar radiation and atmospheric window bands. However, Hu et al. did not consider the radiative properties of the cover of the solar collector/radiative cooler, using polyethylene as cover, which will reduce the efficiency during solar collection mode due to the high emissivity in the near-infrared wavelength (Hu et al., 2016).

The potential of the integration of the RCE novel device into different types of buildings in different climates has been studied elsewhere (Vall et al., 2018).

Solar collectors have been already integrated in many industrial processes in the last years. Over 800 solar thermal plants and more than 1 million m² of solar heat have been reported (Weiss and Spörk-Dür, 2019), many of them in the food industry. Several of these examples of solar collectors integration in industry are investigated in academic papers, such as the combination of solar collectors with heat pumps (HP) in canned fish factories (Quijera et al., 2014); the integration of solar collectors in heat recovery loops of dairy processes (Walmsley et al., 2015); the integration of a concentrating solar thermal plant in a textile factory (Carnevale, 2011); or the large scale solar plants use in copper recuperation processes (Cuevas et al., 2015). The food industry happens to demand both heating and cooling simultaneously. Seven examples of food processes which have been reported to demand both cooling and heating are beer brewing, food pasteurization, fluid milk processing, cheese processing, vegetable and fruit canning, juice canning, and poultry slaughtering (Liu et al., 2016). However, there is no study exploring the industry use of the combined renewable production of heat and cold using RCE devices.

In this paper the potential for integrating the above mentioned RCE technology in the food industry is studied in a monthly and annual basis. Primary energy and cost savings are reported and discussed for the seven industries and for three different climates in Spain.

2. Methodology

First of all, seven food industries (beer brewing, food pasteurization, milk processing, cheese processing, vegetal and fruits canning, juice canning and poultry slaughtering) are analyzed based on the annual loads for heating (hot and warm water) and cooling as well as shown in Table 1 (Liu et al., 2016). The second column, "HP Condenser Cooling needs" refers to the heat that needs to be dissipated in the condenser of the refrigeration heat pump, for the cooling needs of the industry, and assuming a COP of 3. Furthermore, characteristic ratios of heating loads over cooling loads for each industry are identified and can be compared with the RCE ratio of heating over cooling annual production. As the RCE is based on flat plate solar collectors for heating production, and this technology is limited to maximum water temperatures up to 70-80 °C, two industry heating levels are distinguished: industry heating needs over 72 °C, which are not suitable to be covered by the RCE, and heating needs below 72 °C, compatible with RCE temperature levels. Thus, only the primary energy associated to these warm heat demands, normally in the form of hot water, is susceptible to be saved with the RCE integration. As Food pasteurization industry has no warm water needs as shown on Table 1, it will be not included in our analysis. It is observed that poultry slaughtering (with 2881 kJ/kg cold needs and 1800 kJ/kg heat needs) and cheese processing (1343 kJ/kg for cold and 1354 kJ/kg for heat) are the two most energy intensive processes.

Industry process	Cooling needs (kJ/kg)	HP Condenser Cooling needs for COP=-3 (kJ/kg)	Hot water needs (over 72 °C , kJ/kg)	Warm water needs (below 72 °C, kJ/kg)	Ratio total Heating/Cooling industry, η _{tot}	Ratio Warm Water /Cooling industry, η _{warm}	Ratio Warm Water /Condenser Cooling industry, $\eta_{\text{warm,cond}}$
Beer brewing	320	426.7	370	370	2.3	1.2	0.9
Food pasteurization	213.8	285.1	213.8	0	1.0	0.0	0.0
Milk	904.8	1206.4	141.2	141.2	0.3	0.2	0.1
Cheese processing	1343	1790.7	677	677	1.0	0.5	0.4
Vegetable and fruits canning	97.4	129.9	302	302	6.2	3.1	2.3
Juice canning	48.7	64.9	503.4	503.4	20.7	10.3	7.8
Poultry slaughtering	2881	3841.3	900	900	0.6	0.3	0.2

Tab. 1: Heating and Cooling needs per kg of product for various food industries (adapted from Liu et al., 2016).

Second, the monthly and annual production of heat and cold per unit area of RCE can be calculated considering an average daily profile of heat and cold production, based on hourly values of meteorological data, taken from a METEONORM typical meteorological year (TMY) weather files. The heat production is calculated based on the average daily profile of horizontal solar radiation for each month and an average annual value for the efficiency of the RCE in solar thermal collector mode (60%). The cold production is determined based on the net night radiative sky cooling potential (Li et al., 2019) and an average annual RC efficiency (40%) based on recent RCE experimental data (Vall et al., 2020). Three different big and representative cities in Spain with an important food industry activity, namely Seville, Barcelona and Bilbao, are selected for the study. Seville, located in the South, has high solar radiation and high cooling potential, Barcelona, on the Mediterranean See, has intermediate values, and Bilbao, located in the North, has a climate with low solar radiation and low cooling potential. Seville's climate is considered Mediterranean Continental, Barcelona's is Mediterranean Litoral, and Bilbao's Oceanic Litoral. Seville and Barcelona have the same Csa classification (Hot-summer Mediterranean climate) in the Köppen-Geiger climate system, and Bilbao has the Cfb classification (Oceanic climate).

It is important to note here that the RCE is only able to generate cold down to temperatures slightly below ambient (2-8 °C below ambient temperature). As the cooling temperature levels for the food industry is generally in the range 0-15°C (Liu et al., 2016), the cold generated by the RCE cannot replace directly the cooling needs. Instead, it will be used indirectly for the condenser cooling needs of the electrically driven refrigeration heat pump used in the industry to produce the cold-water service. Table 1 includes two columns with this information: the total HP condenser cooling needs (assuming a COP=3) and the ratio of warm water needs over condenser cooling production of the RCE. It is assumed that the condenser temperature with the RCE will be 5 °C lower than the base case operation, thanks to the RCE night radiative cooling. This 5 °C reduction of the condenser temperature will imply a 25% increase in the cooling COP (about 5 % improvement per 1 °C reduction in the evaporator-condenser temperature lift). Note as well that a full coverage of the HP condenser cooling needs by the RCE cooling production implies only 20% savings in the HP electricity consumption (associated to the 25% improvement of the COP mentioned before), not the ideal 100% electricity replacement if the temperature levels produced in the RCE were suitable for the food industry needs.

Third, the sizing of the RCE field is carried out for these extreme cases:

- 1. dimensioning the RCE field for covering all the warm water industry loads in the month with the highest solar radiation (heat tracking sizing).
- 2. dimensioning the RCE field to cover all the heat pump condenser cold needs associated to the industry cooling requirements in the month with the highest radiative cooling potential (cold tracking sizing).

Note that the cooling needs of the condenser are higher than the refrigeration output in the evaporator of the heat pump, as the condenser needs to dissipate both the evaporator load and the compressor work. For example, if we assume a HP cooling COP of 3, the condenser cooling load is 133.3% bigger than the evaporator cooling production.

Finally, once the two RCE sizing are determined, the monthly heating and cooling coverages of the RCE field (RCE heating and cooling fractions) are calculated, and final energy, primary energy and cost savings are compared with the base case of no RCE integration. Table 2 shows several estimated input data required in the calculations, such as HP refrigeration COP, natural gas boiler efficiency, RCE efficiencies, industry Spanish costs for natural gas and electricity and Spanish pass factors from final to primary energy:

Tab. 2: Input data used for energy and cost savings estimations.

Boiler average annual efficiency	HP cooling average annual efficiency	RCE average annual heating efficiency	RCE average annual cooling efficiency	Cost natural gas (€/kWh) [*]	Cost electricity (€/kWh) **	Conversion factor from final energy to primary energy, Electricity ***	Conversion factor from final energy to primary energy, Natural Gas ***
0.9	3	0.6	0.4	0.05	0.092	2.403	1.195

* ("Precio del kWh de gas natural 2019," n.d.)

** ("PRECIO NETO DE LA ELECTRICIDAD DE USO INDUSTRIAL....," 2021)

*** ("Ministerio para la Transición Ecológica y el Reto Demográfico - Documentos reconocidos," n.d.).

3. Results and discussion

Estimated values for hourly, monthly and annual RCE cold (Figure 1) and RCE heat (Figure 2) generation are presented for Barcelona, as example of results. Similar tables have been generated for the other two Spanish cities in study.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Month	1	2	3	4	5	6	7	8	9	10	11	12	
	31	28	31	30	31	30	31	31	30	31	30	31	
Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
0	30.1	28.5	30.7	29.7	29.8	31.8	33.3	33.4	29.8	27.4	29.6	28.9	
1	29.3	28.1	29.9	29.3	28.9	30.8	32.3	32.4	28.8	26.8	29.1	28.8	
2	28.9	28.1	29.2	28.6	28.2	29.9	31.0	31.6	28.0	26.6	28.8	28.5	
3	28.7	27.7	28.7	28.2	28.1	29.3	30.8	30.9	27.3	26.3	28.4	28.2	
4	28.5	27.5	28.5	28.1	27.8	28.8	30.1	30.6	26.7	26.0	27.8	28.3	
5	28.0	27.1	28.4	27.7	27.5	28.8	29.9	30.1	26.5	25.4	27.4	28.2	
6	27.5	26.7	27.9	27.7	27.7	0.0	30.1	29.6	26.2	25.3	27.1	27.7	
7	27.0	26.7	28.0					0.0	27.5	25.3	27.2	27.6	
8	27.3	27.6									26.4	27.7	
9													
10													
11													
12													
13													
14													
15													
16													
17													
18	0.0	0.0								0.0	0.0	0.0	
19	32.6	30.4	0.0	0.0				0.0	0.0	29.1	31.9	31.3	
20	32.2	29.7	32.9	36.8	0.0	0.0	0.0	0.0	33.0	29.8	31.7	30.7	
21	31.6	29.4	32.3	31.8	33.6	36.9	36.6	38.2	31.7	29.0	31.3	30.6	
22	31.0	29.4	31.9	31.1	32.0	34.9	35.8	36.0	30.9	28.5	30.4	30.2	
23	30.7	29.0	31.1	30.4	30.6	33.5	34.7	34.6	30.4	28.1	29.7	29.4	
Night average													
(W/m2)	29.5	28.3	30.0	29.9	29.4	31.6	32.5	32.7	28.9	27.2	29.1	29.0	
Day total													
(Wh/m2)	413.4	395.9	359.5	329.4			324.5	327.4	346.7	353.7	406.9	406.2	Total year
Month total													
(Wh/m2)	1.28E+04	1.11E+04	1.11E+04	9.88E+03	9.12E+03	8.54E+03	1.01E+04	1.01E+04	1.04E+04	1.10E+04	1.22E+04	1.26E+04	1.29E+05

Fig. 1: Average hourly, daily and monthly cooling RCE production at nights for Barcelona (Spain).

It is observed that the average cooling power in nighttime hours is slightly higher in summer months, although the total monthly cold production is about 40% larger in winter months, as more night hours are available. A total annual cold production of 129 kWh/m² is achievable. Note also that during daytime there is no production of radiative cooling in this study, as solar collection is preferred in daily hours, to meet industry heat needs. During the day, in solar thermal collector mode (Figure 2), both the average heat power and the monthly thermal energy production are much higher in summer months. This difference between winter and summer months is even larger than in a typical inclined solar collector, as the RCE is positioned in horizontal position, to maximize the night radiative cooling production. A total annual heat of 965 kWh/m² is produced. The ratio of heating over cooling RCE production, η_{RCE} , is 7.5. Figure 3 shows the comparison of the RCE combined heating and cooling production in the three selected Spanish cities.

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	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Month	1	2	3	4	5	6	7	8	9	10	11	12	
	31	28	31	30	31	30	31	31	30	31	30	31	
Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
1	. 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
6	0.0	0.0	0.0	0.0	0.8	2.6	1.0	0.0	0.0	0.0	0.0	0.0	
7	0.0	0.0	0.0	8.6	52.0	62.5	54.2	15.5	1.3	0.0	0.0	0.0	
8	0.0	0.2	18.2	92.6	145.6	150.4	147.2	100.6	56.1	16.1	0.5	0.0	
9	4.2	34.9	103.1	183.4	239.4	242.9	252.8	194.5	146.1	96.7	42.8	5.5	
10	74.6	118.6	184.1	277.1	309.9	321.5	347.0	277.1	233.4	170.4	113.9	71.3	
11	138.1	200.6	263.0	345.8	387.8	403.5	422.2	363.0	292.4	239.2	173.8	134.0	
12	187.3	259.6	325.9	371.8	437.2	450.7	472.3	406.3	350.7	288.0	225.9	176.5	
13	218.0	278.0	358.4	401.6	446.4	449.5	494.7	422.0	373.5	309.8	232.7	202.1	
14	229.7	281.7	359.5	408.9	428.4	446.8	484.8	422.5	363.0	295.3	223.7	201.8	
15	197.8	249.6	327.0	376.1	405.3	429.0	448.4	396.9	336.3	255.2	192.9	166.6	
16	148.2	193.0	277.9	321.6	358.3	377.3	389.7	337.5	272.4	187.8	131.9	113.0	
17	77.9	122.0	193.6	236.7	279.8	308.1	317.4	263.8	197.6	109.7	60.9	47.1	
18	4.9	47.1	101.8	150.2	188.3	220.9	226.6	180.6	107.6	33.8	1.7	0.4	
19	0.0	0.8	16.2	61.4	95.7	129.5	130.3	90.4	23.4	0.4	0.0	0.0	
20	0.0	0.0	0.0	1.6	18.2	47.7	46.3	12.4	0.1	0.0	0.0	0.0	
21	0.0	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0	0.0	
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
23	3 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
day average,													
for sun hours													
(W/m2)	128.1	148.8	194.5	231.2	252.9	252.7	264.7	248.8	196.7	166.9	127.3	111.8	
Day total													
(Wh/m2)	1280.6	1786.1	2528.6	3237.3	3793.1	4043.4	4235.3	3483.2	2753.8	2002.4	1400.7	1118.3	Total year
Month total													
(Wh/m2)	3.97E+04	5.00E+04	7.84E+04	9.71E+04	1.18E+05	1.21E+05	1.31E+05	1.08E+05	8.26E+04	6.21E+04	4.20E+04	3.47E+04	9.65E+0

Fig. 2: Average hourly, daily and monthly heating RCE production during the day for Barcelona (Spain).



Fig. 3: Annual Heating and Cooling RCE production in Bilbao, Barcelona and Sevilla (Spain).

Sevilla's weather, with more clear days and nights than Bilbao, implies a 54% increase in RCE heating generation and 23% more cooling production. Barcelona is in between, with 30% more heating and 15% more cooling. Regarding the RCE heating over cooling ratios, the values for Sevilla, Barcelona and Bilbao are 8.3, 7.5 and 6.6, respectively.

The above presented RCE heating over cooling production ratios will be compared with the previously presented food industry ratios for warm water demands over condenser cooling needs (see Table 3). The more similar are these two ratios, the more cost-effective will be the investment in the RCE field, as less RCE production will be

wasted and more energy needs will be covered with renewable energy. The juice canning process is the one with the best match ($\eta_{warm,cond} = 7.8$), while the other food industries show much smaller ratios (between 0.1 to 2.3) than the RCE production ratios (between 6.6 and 8.3). The second-best match is vegetable and fruit canning, with $\eta_{RCE}=2.3$. This mismatch means that if the RCE field is matching the warm water loads (sizing Heat), only a small part of the condenser cooling needs will be covered by the RCE cooling, and the electricity savings will be limited. Primary energy savings will be in this case comparable with the savings produced by a field with the same number of solar collectors, with a modest extra primary savings due to the displaced electricity in the HP for the small part of the day in which the RCE cold production can cover the condenser demands. On the other hand, if the RCE field is dimensioned for covering the condenser cooling loads (sizing Cold), a much larger number of RCE devices are required and a considerably bigger investment and longer paybacks are expected. Besides, this cold tracking sizing will generate a large excess of heating, which will be wasted, unless it could be sold to a nearby industry or city. Moreover, larger primary energy and annual cost savings are expected with this sizing, as all the natural gas consumption in the boiler will be displaced by the RCE heating production, and the maximum possible electricity displacement in the HP compressor consumption will be also achieved (20% for a HP COP = 3).

Industry process	Ratio Warm Water /Condenser Cooling industry, ŋ _{warm,cond}	Ratio Heating/Cooling RCE, η _{RCE}
Beer brewing	0.9	6.6 - 8.3
Milk	0.1	6.6 - 8.3
Cheese processing	0.4	6.6 - 8.3
Vegetable and fruits canning	2.3	6.6 - 8.3
Juice canning	7.8	6.6 - 8.3
Poultry slaughtering	0.2	6.6 - 8.3

Tab. 3: Comparison between heat over cold demands ratios in food industry and the expected RCE production ratios.

Figure 4 shows the monthly percentage of warm water needs covered by the RCE production in Barcelona. As the heat tracking dimensioning is done for the month with the largest solar radiation, in winter months the coverage is below 40%. The coverage in July is slightly above 100% due to the rounding-up in sizing the number of RCE units. Figure 5 shows the monthly percentage of condenser cooling needs covered by the RCE production in Barcelona, with the same heat tracking sizing. As anticipated before, only the two canning processes can cover an important amount (above 20%) of their condenser cooling needs. The rest of the food industries included in this study are below 10% for RCE condenser cooling coverage. Similar plots are generated for Seville and Bilbao with similar final results.



Fig. 4: Monthly coverage of food industry warm water with RCE field for heat tracking sizing in Barcelona.



Fig. 5: Monthly coverage of food industry condenser cooling with RCE field for heat tracking sizing in Barcelona.

In Figure 6 the percentages of monthly cold coverage when the RCE field is tracking the HP condenser cooling needs are presented. Contrary to the previous case, now the number of RCEs is much bigger, and the percentage of condenser cooling covered by the RCE is much higher. However, the monthly RCE generation of warm water is well above the warm water needs of all the food industries, so 100% coverage is reached every month, but most of the generated solar heat is wasted (figure not shown).



Fig. 6: Monthly coverage of food industry HP condenser cooling with RCE field for tracking cold sizing.

A reference value of 1 million kg of product per year is considered for the dimensioning exercise as base of calculation. Table 4 presents the percentages of total heat, warm water, HP cooling savings as well as the number of RCE needed in Barcelona for the two selected sizing options: 1) tracking warm water needs (fewer number of RCEs); and 2) tracking condenser cooling needs (greater number of RCE units). The final number of RCE units depends on the location/climate and the sizing, as expected. Putting the focus on juice canning, the food industry best fitting the RCE integration, and in the case of tracking heat, Sevilla needs only 39 units, Barcelona 46 (Table 4), and Bilbao 59. So, better paybacks are expected in Sevilla, as the same renewable heat and cold production can be achieved with less initial investment. The final number of RCE units for heat tracking, and 60 for cold tracking). Other important aspects can be highlighted: the heating savings can only go up 50%, as the other half of the heating needs is at higher temperature and a boiler is still needed. Furthermore, the maximum electricity savings are poor, as we are not able to displace the cooling needs directly with the RCE, but only improve the cooling HP COP thanks to the reduction of condenser working temperature. Similar results are found for Seville and Bilbao.

	RCE Siz	zing Tracking	Warm Water	needs	RCE sizing Tracking Condenser Cooling Needs					
Industry process	% total heat RCE	% Warm Water RCE	% HP cooling electric savings RCE	No RCEs	% total heat RCE	% Warm Water RCE	% HP cooling electric savings RCE	No RCEs		
Beer brewing	31.9%	63.7%	1.5%	34	50.0%	100.0%	17%	393		
Milk	31.9%	63.8%	0.2%	13	50.0%	100.0%	17%	1111		
Cheese processing	31.2%	62.5%	0.6%	61	50.0%	100.0%	17%	1649		
Vegetable and										
fruits canning	32.1%	64.3%	3.9%	28	50.0%	100.0%	17%	120		
Juice canning	31.7%	63.4%	12.9%	46	41.3%	82.6%	17%	60		
Poultry										
slaughtering	31.2%	62.4%	0.4%	81	50.0%	100.0%	17%	3536		

Tab. 4: Differences in sizing the RCE field for tracking heat needs or tracking cold needs in Barcelona.

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Figure 7 shows the comparison of the annual energy costs (warm water and cooling) for the 6 food industries in study. Other high temperature heating costs which cannot be replaced by RCE or other electric costs not associated to cooling needs are not considered in our simulation. Together with the base case costs, costs for the two sizing scenarios (heat and cold tracking) are also presented. Results shown are for Barcelona, but very similar results are obtained for the other two cities under study. The most energy intensive food industries are poultry slaughtering (52,000€ in energy costs for an annual production of 1 million kg of product) and cheese processing (32,000€). Vegetable canning $(10,000\epsilon)$ and milk $(12,000\epsilon)$ process show the smaller energy costs in the base cases. Dimensioning the RCE field for covering warm water needs (Heat tracking case) brings important cost savings. Absolute cost savings happen in the most energy intensive food industries, 17,000€ in poultry slaughtering and 13,000€ in cheese processing. The contribution of electricity cooling cost savings in this case is very small, below 1%. In relative values, the range of cost savings is between 23% and 62%. As discussed above, the largest cost savings in relative terms occur for juice canning process (62%), as its heat and cold needs matches the heat and cold production of the RCE (see Table 3). Even larger cost savings are observed for the condenser cooling tracking case, as many more RCE units are put in the system, and all the industry heating needs are covered in this case. About 32,000€ and 23,000€ can be saved in poultry slaughtering and cheese processing, respectively. For this case the electricity cost savings are noticeable, contributing about 10% of the total savings. Relatively speaking, important percentages of cost reductions are observed for all food industries, ranging from 47% for milk industry up to 93% for vegetables and fruits canning. However, these bigger cost savings are associated to a much bigger initial investment in the RCE field, which discards its economic viability. Assuming a turn key investment cost for the RCE field of 770 €/m² ("Europe," n.d.), reasonable payback periods of 7.2 years are obtained for the heat tracking case



Fig. 7: Annual energy costs for base case, RCE heat tracking and RCE cold tracking in Barcelona.

Table 5 presents the summarized data of primary energy and cost savings in relative terms for the 6 food industries in the three Spanish locations in study. The three cities show very similar results, with differences in cost and primary energy savings of less than 1%. As expected, Sevilla location outperforms Barcelona, and Barcelona has slightly better results than Bilbao. On the other hand, there would be important differences in initial investments due to different sizing results, as stated previously. Cost savings are between 1 or 2 points above primary energy savings, reflecting the higher cost per kwh of electricity over natural gas.

		Heat tracking						Cold tracking					
		Primary enegy savings (%)			Cost savings (%)			Primary enegy savings (%)			Cost savings (%)		
villa	Industry	Gas	Elec.	Total	Gas	Elec.	Total	Gas	Elec.	Total	Gas	Elec.	Total
	Beer brewing	64.3%	1.4%	51.3%	64.3%	1.4%	52.2%	100.0%	18.1%	83.1%	100.0%	18.1%	84.2%
	Milk	63.9%	0.2%	21.9%	63.9%	0.2%	23.2%	100.0%	18.1%	46.0%	100.0%	18.1%	47.7%
	Cheese processing	64.3%	0.6%	40.4%	64.3%	0.6%	41.7%	100.0%	18.1%	69.3%	100.0%	18.1%	71.0%
Se	Vegetable and fruits canning	65.2%	3.7%	59.8%	65.2%	3.7%	60.2%	100.0%	18.2%	92.7%	100.0%	18.2%	93.3%
	Juice canning	63.6%	12.0%	62.1%	63.6%	12.0%	62.2%	96.2%	18.2%	94.0%	96.2%	18.2%	94.2%
	Poultry slaughtering	63.8%	0.4%	32.7%	63.8%	0.4%	34.1%	100.0%	18.1%	59.7%	100.0%	18.1%	61.6%
			Heat tracking							Cold t	racking		
		Primary enegy savings (%)			Cost savings (%)			Primary enegy savings (%)			Cost savings (%)		
Ja	Industry	Gas	Elec.	Total	Gas	Elec.	Total	Gas	Elec.	Total	Gas	Elec.	Total
<u>o</u>	Beer brewing	63.7%	1.5%	50.8%	63.7%	1.5%	51.7%	100.0%	16.8%	82.8%	100.0%	16.8%	84.0%
ce	Milk	63.8%	0.2%	21.9%	63.8%	0.2%	23.2%	100.0%	16.8%	45.2%	100.0%	16.8%	46.9%
ar	Cheese processing	62.5%	0.6%	39.3%	62.5%	0.6%	40.6%	100.0%	16.8%	68.9%	100.0%	16.8%	70.6%
В	Vegetable and fruits canning	64.3%	3.9%	58.9%	64.3%	3.9%	59.4%	100.0%	16.9%	92.6%	100.0%	16.9%	93.2%
	Juice canning	63.4%	12.9%	61.9%	63.4%	12.9%	62.1%	82.6%	16.9%	80.8%	82.6%	16.9%	80.9%
	Poultry slaughtering	62.4%	0.4%	31.9%	62.4%	0.4%	33.3%	100.0%	16.8%	59.1%	100.0%	16.8%	61.0%
		Heat t			racking			Cold tracking					
		Primary enegy savings (%)			Cost savings (%)			Primary enegy savings (%)			Cost savings (%)		
	Industry	Gas	Elec.	Total	Gas	Elec.	Total	Gas	Elec.	Total	Gas	Elec.	Total
Bilbao	Beer brewing	63.3%	1.7%	50.6%	63.3%	1.7%	51.4%	100.0%	16.2%	82.7%	100.0%	16.2%	83.9%
	Milk	64.1%	0.2%	22.0%	64.1%	0.2%	23.3%	100.0%	16.2%	44.8%	100.0%	16.2%	46.5%
	Cheese processing	62.1%	0.7%	39.1%	62.1%	0.7%	40.4%	100.0%	16.2%	68.6%	100.0%	16.2%	70.3%
	Vegetable and fruits canning	63.5%	4.5%	58.2%	63.5%	4.5%	58.6%	100.0%	16.2%	92.6%	100.0%	16.2%	93.2%
	Juice canning	62.4%	14.8%	61.1%	62.4%	14.8%	61.2%	68.7%	16.4%	67.3%	68.7%	16.4%	67.4%
	Poultry slaughtering	62.1%	0.4%	31.8%	62.1%	0.4%	33.2%	100.0%	16.2%	58.8%	100.0%	16.2%	60.7%

Tab. 5: Primary energy and cost savings in food industry for RCE sizing in heat tracking and cold tracking cases.

Finally, Figure 8 illustrates graphically some of the results presented in Table 5. Namely, the percentage of primary energy savings in Barcelona is plotted for the six industries in study for the RCE heat tracking case. Food industries are arranged in descending order of savings, with milk (22% savings) at the top and juice canning (62% savings) at the bottom. As said before, differences among cities are very small, in the range 0-1%. In the same graph the warm water over condenser cooling needs ratios, $\eta_{warm,cond}$, is included, in the upper horizontal axis. This is to visualize again the correlation between the similarity of RCE (η_{RCE}) and industry ($\eta_{warm,cond}$) heat/cold ratios and the achieved energy and cost savings. For instance, in the milk process, ($\eta_{warm,cond} = 0.1$ vs. η_{RCE} for Barcelona = 7.5), the cooling needs in the condenser are 10 times bigger than the ones for heating. Thus, when the RCE field is covering most of the heating needs, most of the electric needs for cooling are still there, achieving only 22% of total primary energy savings. On the other hand, in the juice canning case ($\eta_{warm,cond} = 7.8$), there is an almost perfect match with the η_{RCE} for Barcelona (7.5). This implies that the RCE field covers an important part of the heating needs (Figure 4) and covers also most of the condenser cooling needs (Figure 5), contributing with almost 13% in electricity cooling savings. Thus, total primary savings reach 62% for this industry.



Fig. 8: Primary energy savings in food industry for the RCE heat tracking case in the Bilbao, Barcelona and Seville.
4. Conclusions

The potential of the integration of a novel renewable heating and cooling technology (RCE) in seven food industries (beer brewing, food pasteurization, milk processing, cheese processing, vegetal and fruits canning, juice canning and poultry slaughtering) has been studied. Two different sizing matching the heat needs and the cooling needs have been considered. The number or RCE devices depend on the location and is for the two considered scenarios very different, with larger investment for the cooling sizing. Comparing the ratios of heating over cooling loads in several processes with the ratios of RCE heat and cold production, best matches are found for vegetable and fruits and juice canning industries. Moreover, primary energy savings reach 62% for the juice canning industry as the RCE field covers an important part of the heating and of the condenser cooling needs.

5. Acknowledgments

The work was partially funded by the Spanish government under grant agreement RTI2018-097669-AI00 (Ministerio de Ciencia, Innovación y Universidades). The authors would like to thank Generalitat de Catalunya for the project grant given to their research group (2017 SGR 659).

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I-02. District Heating

Investigating Measures on Space Heating and Domestic Hot Water Preparation Systems in Residential Buildings Regarding their Impact on the Total Heat Demand and Return Temperatures in District Heating Networks

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Abstract

District heating can contribute substantially to a cost-effective decarbonization of the heating sector. Lowering the temperature levels of district heating systems is an important requirement for the efficient utilization of renewable energy sources. As return temperature reductions must precede flow temperature reductions, the consumers in a district heating system play a major role. This simulation study takes a closer look at four exemplary buildings space heating and domestic hot water preparation systems using TRNSYS and investigates influences on the total heat demand and return temperatures. In buildings with high energy efficiency standards the domestic hot water preparation makes up about half of the total heat demand and therefore has a very high impact on the total return temperatures. By reducing the circulation heat losses and switching from storage systems to instantaneous domestic hot water preparation, return temperatures can be reduced significantly. In existing buildings, with higher space heating demand, the space heating system design is a key driver for the total return temperatures. However, user behaviour and especially faults, like unnecessary bypasses also have significant influences and can raise return temperatures.

Keywords: Space Heating, Domestic Hot Water, District Heating, Return Temperatures, Heat Demand

1. Introduction

District heating (DH) systems allow to efficiently utilize renewable heat sources as well as excess heat for the supply of space heating (SH) and domestic hot water (DHW) in buildings. They are more cost-effective for densely populated areas and often more environmentally beneficial (Lake et al., 2017). Because of the aforementioned reasons, Werner (2017) concludes that DH systems have strong potential to be a viable heat supply in the future world. Nonetheless, currently district heating covers only approximately 13 % of the total heat demand of buildings in the European Union (Averfalk et al., 2021). Paardekooper et al. (2018) state that the further extension of thermal grids in Europe is substantial to enable better integration of excess heat sources and renewable heat. In addition to the further extension, lowering of supply temperature in DH grids facilitate the integration of these sources and increases energy efficiency (Averfalk et al., 2021). Lowering temperature levels often also involves reduced investment and operation cost. In existing DH networks a cost reduction gradient of about 0.11 to $0.49 \ \text{€/(MWh}^\circ\text{C})$ could be found, while future economic benefits are estimated at about $0.50 \ \text{€/(MWh}^\circ\text{C})$ (Averfalk et al., 2021).

In contrast the temperature levels during operation of present DH systems are on average about 10-15 K higher, compared with achievable temperature levels (Averfalk et al., 2017). This can be due to errors in customer substations or heating systems, which increase the return temperature and in turn result in higher supply temperatures (Averfalk et al., 2017, 2021). Hence, the customer installation and substation limit the opportunities to lower the DH network temperatures. Østergaard and Svendsen (2018) investigated heating system operation and occupant behaviour in five Danish single-family houses. Results showed that incorrect heating system design and control as well as occupant behaviour can cause higher return temperatures.

Best et al. (2020) assessed the impact of building systems engineering and building density on the return temperature for newly constructed districts and concluded that instantaneous DHW preparation achieves lower return temperatures. In addition, districts with higher building density show lower total return temperatures.

Benakopoulos et al. (2021) gave an overview of solutions to achieve low return temperatures in DHW preparation systems with circulation. They identified minimizing the circulation heat losses as a key requirement for low return temperatures and made recommendations for the design of DHW preparation systems. Østergaard et al. (2021) investigated ten Danish buildings that showed low return temperatures in measurements and found that the single-family houses with the lowest return temperatures (25-30 °C) did not have DHW circulation systems.

In the present work, the impact of measures and user behaviour on the total heat demand and mean return temperature of four exemplary buildings is investigated. The buildings as well as SH and DHW systems are modelled and simulated. Two buildings represent existing single family (SFH) and multi-family houses (MFH), which have been partly refurbished. The other two buildings are the same SFH and MFH but considered as new buildings, with a high energy efficiency standard. The impact of measures and behaviour changes on the SH and DHW preparation systems are examined for the building types. Furthermore, the differences between the building types, regarding these parameters, are highlighted.

2. Simulation Models and Reference Conditions

This section gives an overview of the simulation models and reference conditions, which are used for the study. Two separate simulation models are developed for building and SH demand (2.1) and DHW preparation (2.2). Section 2.3 covers the methodology for the aggregation of simulation results of both models and the consideration of possible bypass flows. Fig. 1 shows a simplified hydraulic scheme of the whole system.



Fig. 1: Hydraulic scheme of the reference substation, space heating and domestic hot water preparation systems

2.1. Building and space heating

Two different residential buildings are generically designed and equipped with two different thermal envelope standards, resulting in four simulations models, which are modelled in TRNSYS 18 (University of Wisconsin, 2017). The building and flat layout is based on statistical data from the German federal office of statistics, while the thermal envelope is dimensioned according to literature values of existing buildings (Loga et al., 2012) or regulation for newly constructed buildings. The first type of building envelope called "refurbished" depicts an existing building in Germany with refurbished windows, roof and basement ceiling. For the second thermal envelope type the efficiency standard "new" is selected, which resembles a newly constructed building with even better structural quality of the building envelope ("KfW Efficiency Building 55") compared to the current minimal requirements given by the current German Building Energy Law (GEG, 2020). Tab. 1 gives general information and heat transmission coefficients of the buildings. The weather data acquired from the German weather service

depicts a test reference year of Mannheim, Germany referring to the years 1995-2012.

Each building model is divided into thermal zones within TRNSYS. The SFH consists of eight thermal zones on two floors. The MFH is split into 16 thermal zones on four floors, each zone resembling a whole flat with a living area of 72 m². In addition, a not-heated stairwell is included in the center of the MFH building. Each thermal zone, except the hallway, is equipped with one SH device including a thermostatic valve (THV) modelled as purely proportional controller (TRNSYS-Type 1669). In the refurbished buildings these devices are convectors (Type 362) with a proportional band of 2 K, while all newly constructed buildings are heated by floor heating systems (Type 653) with a proportional band of 1 K. The SH devices are dimensioned in a common way by using the German norm DIN 12831-1 that takes the worst-case outdoor conditions, infiltration and ventilation air change rate as well as a room set point temperature of 20 °C as input. Design temperatures for the convector are 65/45 °C and for floor heating 35/25 °C. The pipe length and diameter are estimated in accordance with the German norms DIN 18599-5 and DIN 1988-300, respectively. The pipework is modelled with Type 604. The supply temperature of the heating system is controlled by a linear heating curve depending on the outdoor temperature. In Addition, internal heat gains by inhabitants as well as technical devices in accordance to German norm DIN 18599-10 are considered in the building model. Internal heat gains by humans are considered independently of the actual number and presence of inhabitants and add up in SFH and MFH to 45 and 90 Wh/(m²·d), respectively. Technical devices are assumed to constantly deliver 12 Wh/(m²·d).

Tab. 1: Parameter of the building model. Aenv: Building envelope area; Vgross: Gross volume of building;
H' _T : Resulting total specific transmission coefficient for heat-transferring enclosing surface

General Information	B1	B2	B3	B4	
Building Type		SFH		MFH	
Number of housing units		1	16		
Gross living area in m ²		177		1,257	
Aenv/Vgross		0.63		0.3	
Building envelope standard	Refurbished	New	Refurbished	New	
Q _{sh} in kW (DIN 12831-1)	14.3	5.7	57.5	22.4	
Heat transmission coefficients in	W/(m²·K)				
Outer walls	1.42	0.2	1.42	0.2	
Windows (U _w)	1.3	0.95	1.3	0.95	
Roof	0.3	0.12	0.3	0.12	
Basement ceiling	0.3	0.22	0.3	0.22	
Total coefficient H' _T	0.93	0.31	1.16	0.39	
Infiltration and Ventilation					
Air change rate by Infiltration	n = 0.14	n = 0.07	n = 0.14	n = 0.07	
Window ventilation	Yes	Yes	Yes	Yes	
Air change rate through window	n = 0.5	May-Aug: n = 0.5 Sep-Apr: n = 0.1	n = 0.5	May-Aug: n = 0.5 Sep-Apr: n = 0.1	
Air ventilation system	No	Yes	No	Yes	
A in show so note		May-Aug: $n = 0.0$		May-Aug: $n = 0.0$	
An change rate	-	Sep-Apr: $n = 0.4$	-	Sep-Apr: $n = 0.4$	
Heat recovery	No	Yes (0.8)	No	Yes (0.8)	

2.2. Domestic hot water preparation

The useful energy demand for DHW is calculated as a function of the buildings living area as defined in the German norm DIN 18599-10. The energy demand is converted into a mean daily draw-off volume, which is entered as input into the program DHWcalc (Jordan and Vajen, 2001). DHWcalc is used to generate draw-off profiles in a 3-minute time step, which are read into the simulation model that simulates the DHW preparation systems.

As the reference system, a storage system is chosen according to Fig. 1. The storages are dimensioned according to the German norm (DIN 4708). As indicated in Fig. 1, two temperature sensors are installed inside of the storage. One sensor is placed at the top of the storage. When the temperature at this sensor drops below 60 °C, the pump in the charging cycle for the storage is switched on, which charges the storage with a constant mass flow. The

pump is switched off when the temperature at the second sensor, which is placed at 20 % of the storage height, is above 60 °C. The storage is modeled with a stratified storage model (Drück, 2006). The heat loss coefficient is calculated according to the EU's energy efficiency label (European Commission, 2013). For the reference case an efficiency label class B storage is chosen. The resulting heat loss coefficient is multiplied with a correction factor of 1.2 to into account take possible installation errors of the insulation.

A DHW circulation system is considered in all buildings. In the SFH, the circulation system is installed between the substation and every draw-off point. In the MFH, only the supply towards every living unit is part of the circulation system. The distribution pipes inside the living units are not part of the circulation system. The return temperature of the circulation system is set to 55 °C, which is a requirement of German regulation for the prevention of legionella (DVGW, 2004). The circulation return is not connected to the storage but flows directly into the heat exchanger (see Fig. 1). In the reference case, the circulation system is operated constantly, without interruption. The pipe lengths are estimated according to a study conducted in Germany by Jagnow et al. (2010). The dimensioning of the distribution and circulation pipes is carried out by the same methodology described by Braas et al. (2020). The heat exchanger for the DHW preparation system is dimensioned for the simultaneous operation of the storage charging cycle and the circulation system. A temperature difference of 3 K between the outlet temperature on the hot side and the inlet temperature on the cold side is considered for the dimensioning of the attemption of the reference DHW preparation system are summarized in Tab. 2.

Building	SFH	MFH
Occupants	3	29
Specific DHW demand in kWh/(m ² ·a)	8.5	12.9
DHW demand at 60 °C in l/d	65	702
Storage volume in l	120	400
Storage heat loss rate in W/K	1.9	2.9
Storage charging flow rate in l/h	60	230
Circulation flow rate in l/h	34	209
UA-Value HX in W/K	764	3,019
DHW peak load in kW	3.9	15.4

ſab.	2:	Parameters	for	reference	DHW	preparation	systems
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2.3. District heating grid, result aggregation and primary bypass

As this work concentrates on heat supply systems within buildings, the district heating grid is not part of the simulation models. Nevertheless, a district heating supply temperature had to be determined to investigate the thermal behaviour of the substations and heat supply systems in buildings. A generic low-temperature district heating grid with a supply temperature of 70 $^{\circ}$ C at the substation is assumed. This supply temperature is high enough to both supply SH for the refurbished existing buildings and guarantee hygienic requirements of DHW. The supply temperature is assumed constant during the year.

The simulation results yield mass flowrates and return temperatures on the primary side of the two separate heat exchangers. To calculate total return temperatures these mass flows are mixed (eq. 1).

$$T_{return,tot} = \frac{T_{return,dhw} \cdot \dot{m}_{dhw} + T_{return,sht} \cdot \dot{m}_{heat}}{\dot{m}_{dhw} + \dot{m}_{heat}}$$
(eq. 1)

To assess influences on the total return temperature, a yearly mean return temperature is calculated by weighting every time step's return temperature with the corresponding total mass flow rate (eq. 2)

$$\bar{T}_{return} = \frac{\sum_{t=1}^{t_{end}} (T_{return,tot,t} \cdot \dot{m}_{tot,t})}{\sum_{t=1}^{n} \dot{m}_{tot,t}} \quad \text{with} \quad \dot{m}_{tot,t} = \dot{m}_{dhw,t} + \dot{m}_{heat,t} \quad (eq. 2)$$

In periods with no or low demand, the house connection pipe and fluid can cool down. This can result in lower DHW preparation comfort as hot water preparation takes longer, especially if instantaneous DHW preparation is considered (see section 3.2). This issue can be solved in practice, by installing a primary bypass, which increases the supply temperature in the pipe in periods with low demand by using a bypass flow (Brand et al., 2014). The

effect of such a primary bypass on the total return temperatures is estimated by considering house connection pipes, with a length of 20 m in each building. The pipes are dimensioned considering the peak load of each building. A high insulation standard (series 3) is considered. The necessary bypass mass flow is a function of the heat loss of the supply pipe and the bypass set temperature, which defines the lowest allowed temperature at the heat exchangers. The set temperature is varied to assess sensitivities. The pipe dimensions and specific heat loss ratios are given in Tab. 3.

 Tab. 3: Pipe dimension and specific heat loss ratio for house connection pipes. The specific heat loss ratio is in relation to the temperature difference between the DH medium and surrounding ground temperature.

	SFH New	SFH Refurbished	MFH New	MFH Refurbished
DN	20	20	20	25
Insulation thickness in mm	49.0	49.0	49.0	45.7
Spec. heat loss ratio in kW/K	1.98	1.98	1.98	2.30

3. Investigated Measures and Influences

In this section the investigated measures and influences on the SH (3.1) and DHW (3.2) systems are described.

3.1. Space heating system

Measures examined for the SH system include user behaviour and system design. First, the impact of occupant behaviour on return temperatures and heat demand is assessed. Second, the influence of a neglected residue of older heating systems on a DH substation is tested, which is a realistic case after conversion of the heat generation unit (Averfalk et al. 2017).

1. Variation of user behaviour: room set point temperature

User behaviour is without doubt an unpredictable influence factor on heating systems and therefore on district heating systems (Østergaard and Svendsen, 2018). Consequently, the influence of an increasing room set temperature is examined. In four separate steps, the set point temperature is increased from 20 °C in the reference scenario in 1 K steps up to 24 °C. The room set temperature is changed in the thermostatic valve which every SH device is equipped with. Each room set point temperature is kept constant during the year.

2. Variation of user behaviour: window ventilation

Additionally, the influence of increased and decreased ventilation through windows is examined. The air change rate of the reference scenario is first doubled and then halved. The air change rate through windows in winter is assumed to be lower than in the refurbished buildings (see Tab. 1), because the new buildings are equipped with a mechanical ventilation system with heat recovery. Accordingly, the hourly air change rates in winter differ from the air change rates in summer in the new buildings. Tab. *4* shows an overview of the applied air change rates per building standard.

Tab. 4: Air change rates of the different buildings in the reference scenario compared to the measures concerning ventilation through windows.

Air change rate in h ⁻¹	Reference scenario	Measure 1	Measure 2
Refurbished Building	0.5	1.0	0.25
New Building	May-Aug: 0.5 Sep-Apr: 0.1	May-Aug: 1.0 Sep-Apr: 0.2	May-Aug: 0.25 Sep-Apr: 0.05

3. Secondary bypass

Old heating systems in existing buildings using an oil boiler is usually equipped with a three-way diverting valve which maintains a certain return temperature to the heat generation unit (Averfalk et al., 2017). As reported by Averfalk et al. (2017) the removal of this diverting valve may have been overlooked in some cases. Accordingly, a hot short-circuit flow passes the thermostatic controlled valve and keeps the return temperature above a certain temperature. The former purpose of these valves was to maintain a certain temperature in the combustion chamber and therefore avoid condensation inside the boiler. However, in SH systems supplied by DH this is an unfavorable feature, which will lead to elevated primary return temperature. In the TRNSYS models a thermostatic controlled

valve is implemented on the secondary side to maintain a return temperature of 50 °C. As this scenario is only likely to happen in existing buildings this feature is only examined in models with refurbished buildings.

3.2. Domestic hot water system

The investigations for the DHW preparation systems include changes to the circulation system control as well as pipe and storage insulations. Additionally, the influence of substation design and design temperatures on return temperature and heat demand is assessed.

1. Circulation Shutdown

For this measure, the circulation system is shut down for 6 hours between 11 pm and 5 am. For houses with more than two living units, German regulations (DVGW, 2004) allow the circulation system to be shut down for a maximum of 8 hours per day. Compared to the reference case this measure is expected to reduce the heat losses of the circulation system by approximately 25 %, as the system is shut down for ¹/₄ of the time. As the circulation system is generally causing high return temperatures, reducing the operation time should also lead to reduced total return temperatures.

2. Ideal Circulation

For this measure it is assumed, that the user activates the circulation system, before tapping hot water. In the simulation, the circulation system runs for one time step before every draw-off occurrence. This measure is only considered in the SFH, as it does not conform with German regulations (DVGW, 2004) for MFH. It is expected that the heat losses of the circulation system, as well as the return temperatures of the total DHW preparation system will be drastically reduced, as the circulation period is much shorter.

3. Increased Pipe Insulation

As stated before, the distribution and circulation pipes for DHW are insulated according to the German building code (GEG, 2020). For this measure, the pipe insulation thickness is doubled. By this, the heat losses of the distribution and circulation should be reduced, which is expected to reduce the heat demand and yield lower return temperatures.

4. Increased Storage Insulation

For this measure, the storage (efficiency label B) is replaced by a storage with a higher level of insulation (efficiency label A). Thus, it is expected that the storage heat losses will be reduced by more than 50 %. As the heat demand for storage heat losses must be met at high temperatures, it is also expected, that return temperatures will be reduced. However, the effect will probably be neglectable in the MFH, as the storage heat losses are very low compared to the total heat demand for DHW.

5. Two Stage Heat Exchanger

Examples from literature (Zeisberger, 2017; Johansson et al., 2009) show that by using two heat exchangers for DHW preparation, return temperatures can be reduced, because the primary flow that reheats the return of the circulation system can be cooled down by DHW demand (Fig. 2). shows a hydraulic scheme. This measure is only considered in MFH, as the added complexity is expected to exceed the benefits in SFH.

6. Instantaneous DHW Preparation

Instead of charging a storage, DHW can be heated instantaneously by a heat exchanger. This setup leads to much larger heat exchangers and peak loads but promises lower return temperatures as shown by Best et al. (2020). For the SFH, the peak load increases to 34 kW. For the MFH the increase is lower (100 kW), because of simultaneity effects. The increased peak load is also taken into account





for the dimensioning of the house connection pipes, which are considered to assess the influence of bypass flows. For the SFH the house connection pipe dimensioned stay unchanged. For both MFH DN32 pipes with a specific heat loss of 2.51 kW/K must be installed.

7. Reduced Supply Temperature

The DHW supply temperature of 60 °C is required for hygienic reasons (legionella). German regulation (DVGW, 2004) however does not make requirements if the total DHW systems pipe volume is below 3 liters. This can be achieved by separating the supply towards and the distribution inside apartments of the MFH with additional heat exchangers. This decentralized DHW system is investigated for the new MFH. The flow temperature of the DH system is assumed 55 °C at the substation instead of 70 °C during the reference scenario. Inside the building, the set point temperature in the storage is set to 48 °C, while the DHW is supplied at 45 °C inside the apartments. For the new SFH a supply temperature of 45 °C is also assumed. As the regulations do not apply in SFH, no additional heat exchangers are needed. As the circulation system is running at much lower temperatures, it is expected that both the heat demand as well as the return temperatures will be reduced for these systems.

4. Results & Discussion

4.1. Final Energy Demand

On the top of Fig. 3 the yearly mass flow weighted return temperatures for the SH system, the DHW preparation system as well as the total mixed return temperature (see eq. 2) are depicted. On the bottom the specific heat demand for each building type is shown. The heat demand is composed of useful energy demand and heat losses for each SH and DHW.



Fig. 3: Simulation results for all reference buildings. Top: Yearly mass flow weighted mean return temperatures for SH, DHW and total. Total return temperature without (black) and with bypass influence (orange). Bottom: Specific heat demand divided into SH and DHW demand as well as useful energy and heat losses

For SH in the new buildings the heat losses are a rather small portion of the total heat demand (7 to 9 %). In the refurbished buildings, the heat losses represent a higher share (16 to 21 %). For DHW the heat losses make up 56 to 64 % of the total DHW demand. In the MFH the storage heat losses are marginal compared to the total DHW heat demand (2.6 %).

Looking at the return temperatures it is obvious that the DHW systems have very high return temperatures (48 to 54 °C). As the MFH are more densely populated, the share of circulation heat losses, which cause high return temperatures, is lower compared to the SFH. Thus, the return temperatures in the MFH are lower than in the SFH. The SH return temperatures are dependent on the heating system: in the new buildings, the floor heating system yields very low return temperatures at about 25 °C. In the refurbished buildings with convectors, the return temperatures are higher (34 to 38 °C). The total return temperatures are closer towards the SH return temperatures in the refurbished buildings because the SH system has a much higher (77 to 85 % of total heat demand) energy

demand than the DHW system (15 to 23 %). In the new buildings, the DHW systems are dominating the total return temperatures. This is because the energy demands are at about the same level (DHW: 43. 65 %; SH: 35 to 57 %), but because of the high return temperatures, the DHW has much higher mass flows. The influence of the bypass is neglectable in all reference cases, since the circulation systems are always running.

4.2. Measures on the space heating system

Fig. 4 shows the resulting return temperatures and specific heat demands of five measures on the SH system for the refurbished SFH and MFH, respectively, compared to the reference scenario. With increasing room set point temperature up to 24 °C (see no. 1a, b) there is a clear trend to increasing primary return temperatures in existing refurbished SFH and MFH. The increase from 20 to 24 °C room set temperature results in a total increase of the primary return temperature of the SH heat exchanger of 7.2 K in SFH and 6.6 K in MFH. This indicates a rising return temperature of approximately 1.7 K per 1 K increase of the room set point temperature. Whereas the total primary return temperature increases slightly less by 4.3 and 3.7 K in SFH and MFH, respectively. Additionally, the specific heat demand rises, which is, in combination with increasing return temperatures, the worst case for a DH network.



Fig. 4: Return temperatures and specific heat demand of reference scenario compared to different space heating measures in the existing refurbished SFH and MFH.

An explanation for this are the undersized SH devices for this load, leading to insufficient cooling of the SH mass flow. SH devices were originally designed to heat the room to 20 °C. Consequently, the insufficient cooling of the mass flow results in rising primary and secondary return temperatures. The heat transferring power of SH devices is essentially dependent on the heat transferring area and the temperature difference between the device and the room air. Increasing the room set point temperature at the thermostatic valve (THV) increases the valve opening. As a result, the THV closes slower depending on the room air temperature. A high mass flow but not enough power due to lower temperature difference leads to insufficient cooling of the mass flow and increasing heat demand. A similar case occurs when the actual ventilation through windows is higher than assumed during the dimensioning process (see no. 2a, b). Although there is a slightly lower mean room air temperature over the year and therefore, the temperature difference of SH device and room air temperature is higher, the mass flow running through the SH device cannot be sufficiently cooled. This discrepancy indicates that the configuration of the THV plays a crucial role. Østergaard und Svendsen (2018) also conclude that improper mass flow can cause higher return temperatures. Reversely, the primary and secondary return temperature decreases with lower ventilation. In this case, the partial load results in stronger cooling of the SH mass flow compared to the reference scenario leading to lower return temperatures. For the new buildings, the reported findings for the measures are similar when comparing the SH return temperature, but not when comparing the total primary return temperature. The total primary return temperature falls when a higher room set temperature is applied, because the share of SH demand in total heat demand increases. As the return temperature from floor heating is only around 25 °C, the higher influence of SH lowers the total return temperature but increases the heat demand. As the new building is equipped with a mechanical ventilation including heat recovery, the influence of higher or lower ventilation is practically not given.

The effect of a secondary bypass shows a slightly increased heat demand as well as a return temperature constantly around the set point of the bypass (see no. 3). In the analyzed case, the set point is set to 50 $^{\circ}$ C, which is close to the reported mean return temperature.

4.3. Measures on domestic hot water system

Fig. 5 shows the results for the measures on the newly constructed SFH. The measures are numbered according to the numeration in the previous section. The results A, B and C represent combinations (see Fig. 5) of different measures. The results show that the circulation shutdown and increased pipe insulation have similar effects (see no. 1 and 3). The circulation heat losses are reduced, which also leads to reduced total return temperatures. For the storage system, the largest impact is reached by the ideal circulation (no. 2), which leads to a total return temperature below 40 °C. Increasing the storage insulation (no. 4) also reduces the energy demand and yields a small return temperature reduction (1.7 K). By combining the measures for the storage system (A), the total heat demand can be reduced by 21 % and the total return temperature reduced by 12 K.

Changing to instantaneous DHW preparation (no. 6) reduces the heat demand, as there are no storage heat losses. In the reference case the total return temperature is reduced substantially (-5 K). By adding the ideal circulation and increased pipe insulation (B), the return temperature of the DHW system is reduced below 20 $^{\circ}$ C.



Fig. 5: Simulation results (return temperatures and specific heat demand) for measures on the new SFH

The results of all variants considering a primary bypass show that a bypass flow becomes necessary when the operation time of the circulation system is reduced. For the instantaneous system, the need for a bypass flow is higher. A bypass at a constant temperature of 60 °C would increase the total return temperature for the "ideal" instantaneous system (B) by 6.7 K. Still, the return temperature would be lower than for the storage system.

By reducing the DH supply temperature (no. 7), the return temperature is also reduced because the circulation system is running on lower temperature levels. This also leads to a small reduction (6 %) in the total heat demand. Considering ideal circulation and increased pipe insulation, total return temperatures of approx. 25 °C can be reached. The influence of the bypass is smaller because the heat losses of the house connection pipe are also

reduced due to the lower flow temperature.

For the refurbished SFH, the results are similar. However, because of the high SH demand, the effect on the total return temperature is a lot smaller. The instantaneous DHW preparation with ideal circulation, which has the highest potential to reduce return temperatures, only reduces the total return temperature by 5.4 K (from 42.2 to 36.8 °C). The bypass' influence is also reduced, as the heating period is longer.

The results for measures on the DHW system for the newly constructed MFH (Fig. 6) show the same tendencies as for the SFH. The effects on the total return temperature are higher because the share of DHW on the total heat demand is higher. Reducing the circulation heat losses through circulation shutdown (no. 1) or increased pipe insulation (no. 3) leads to reduced return temperatures. Increasing the storage insulation has almost no effect in MFH. As expected, changing the substation type to a two-stage heat DHW preparation system reduces the return temperature. By combining the measures for the storage system, the return temperature can be reduced by 8.5 K (from 43.5 to 35.1 °C). This also yields a total heat demand reduction of 12 %. An even higher return temperature reduction can be reached with instantaneous DHW preparation (11 K to 27.9 °C). As for the SFH, reducing the supply temperature also yields very low return temperatures of about 25 °C. Because of the more evenly distributed DHW load in the MFH, the primary bypass has very low impact on the results.



Fig. 6: Simulation results (return temperatures and specific heat demand) for measures on the new MFH

5. Conclusions

The relation of DHW to the SH demand highly depends on the building envelope, the SH and ventilation system as well as the relation of envelope area to gross volume of the building (higher in SFH than in MFH). For new buildings, the DHW demand makes up 44 and 66 % of the total heat demand for SFH and MFH, respectively. This has crucial impact on the district heating system supplying these buildings. With a higher share of DHW demand, the heat demand in the summer becomes more important, which for example make higher shares of solar thermal heat supply economically feasible. In addition, the increasing importance of energy efficient DHW systems that yield low return temperatures has to be emphasized, especially with the ongoing improvement of the thermal building envelope.

For all reference buildings, the return temperatures from the DHW preparation system (48 to 54 °C) are higher than for the SH systems (25 to 38 °C). In the refurbished buildings, the SH system is the primary driver of the total return temperatures. In the new buildings the DHW preparation system is the primary driver. Thus, measures on the DHW system have higher influence on the total return temperatures in the new buildings, while in the refurbished buildings measures on the SH system have higher influence. Notably, measures on the SH system that

increase the return temperature as well as the heat demand of the SH system, yield lower total return temperatures in new buildings.

For SH systems in the refurbished buildings, the results show that if the actual heat load is higher than assumed for the dimensioning of the system (due to higher room temperatures or window ventilation) the return temperatures increase significantly. Therefore, considering occupant behaviour in combination with SH system design is essential when low return temperature is the objective. The results for the secondary bypass show that they must be removed to allow the efficient operation of DH systems, when connecting old buildings to a DH network.

The investigated measures for the DHW systems show that the key to reducing return temperatures is reducing the heat losses (storage and circulation) of the system. The best solution for SFH is to omit circulation systems altogether as they are mostly used for comfort reasons. If this is not possible, it is important to find intelligent control solutions that reduce the operation time as much as possible. This can be intelligent controls that learn the user behaviour or technical solutions, which allow the users to activate the circulation system manually. For MFH circulation shutdown times are beneficial. Whether increasing the pipe or storage insulation is economically feasible is not investigated in this work. On the one hand additional costs and potential space requirements must be considered. On the other hand, the end user saves energy costs because of the reduced heat losses. Additionally, the return temperature reduction might favor the DH systems heat supply, capacity and pumping costs.

Switching from DHW preparation systems with storage to instantaneous systems can yield greatly reduced return temperatures, even when a primary bypass is considered. In this case, too, the additional costs (larger heat exchanger, possibly larger house connection pipe) must be weighed against the benefits (lower return temperatures).

By installing decentralized heat exchangers in every apartment of multifamily houses, the supply and return temperatures of DH systems can be reduced without the risk of legionella growth. This can have many benefits for the DH system. However, the additional costs for the heat exchangers could outweigh the benefits.

Acknowledgement

The authors greatly acknowledge the financial support of the project by the German Federal Ministry for Economic Affairs and Energy (FKZ: 03ET1580C).

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Performance of a High Solar Fraction District Heating System

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Abstract

At the end of 2019, a solar district heating system was built in Zhongba town in the west of Tibet. The system includes 32,175 m² of flat plate collectors, 15,000 m³ of storage tank, 103,000 m² of heating area, and a 200-kW PV system. In the 2020-2021 heating season, the solar fraction of the system is 100%. This paper introduces the system characteristics, principles, and running situations and compares the simulated system performance with measured including solar fraction, collector efficiency. The collector array efficiency analysis method is discussed, the storage stratification is shown, and the heat loss factor is defined. The system has a good performance and proves that a high solar fraction district heating system is available in cold and high-altitude areas.

Keywords: Solar district heating, High Altitude, High Solar Fraction, Zhongba,

1.Introduction

The weather is freezing in Zhongba of Tibet, China, where the lowest temperature is lower than -40 degrees, and there is no reliable space heating during the eight months of frigid winter. There is no oil and gas there, and the primary heating material has been cow dung, which is not comfortable for users and is harmful to the environment. Considering the shortage of conventional sources and the rich solar energy, a high solar fraction district heating system was built to solve the heating problem. The construction was started in May 2019, and the system was put into operation in November 2019.



Fig. 1: Location of Zhongba (Source: Google Map)

2.System Description

2.1. System Overview and Parameter

With a total population of about 5,000 people, Zhongba has a total heating floor area of $103,000 \text{ m}^2$, including schools, hospitals, government offices, and residential houses. Carbon steel underground pipeline is laid along the side of the road. The altitude of Zhongba is 4700 m, which means the water will be boiled if the temperature is higher than 85°C if no additional pressure. For safety, low-temperature hot water heat-supply system is designed in Zhongba. The main design parameter is given in Table 1.

Tab. 1: Main design parameter

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Heating period	Total heat load (Design temperature)	Design solar fraction	Supply/return temperature in the city grid	
Nov 1 to 31, May (251 days)	5.8MW (- 21.1°C)	95%	65/35 °C	

High-efficiency flat plate collectors are used with 2340 pieces in total, taking up $32,175 \text{ m}^2$ of total aperture areas. The volume of the storage tank is 15000 m^3 , and the diameter is 28.5 m. Meanwhile, 200 mm glass wool is used for insulation on the side, and 300 mm glass wool is used for insulation on the top.

A 1300 m² building was built for all equipment, including auxiliary heat sources with two sets of 1.4 MW diesel boilers, pump stations, heat exchange units, power distribution systems, and generators. Considering the lack and instability of local power, 200 kW photovoltaic power generation has been built, which is used in conjunction with municipal power and diesel generators. To solve the overheating problem, the system is equipped with three sets of 2 MW dry coolers. The project view is shown in Figure 2.



Fig. 2: Aerial view of the project

2.2. Brief Introduction of System Operation Logic

The system schematic is shown in Figure 3. When the solar radiation reaches a specific value or the temperature in collectors is higher than certain degrees, the solar circulation system will start to transfer heat to the tank. The speed of pumps is controlled by solar radiation to make the outlet temperature of solar collectors more stable. Hot water for space heating will come from the top of the tank. If the forward temperature is high enough, the water from the top of the tank will be mixed with water returned from the city grid or water in the middle of the tank to make the forward temperature stay at a suitable value. When the water temperature in the tank is low enough, the oil boilers start to work.



Fig. 3: System schematic diagram

The system is equipped with dry coolers to dissipate heat when the system is overheated. It is dangerous when the

bottom of the tank is at a high temperature. The system will start the protection mode to discharge heat by the solar collectors at night. When the temperature in the collector or the ambient temperature is lower than the set value, the antifreeze protection will start to work. The schematic system diagram is shown in Figure 3.

3.System performance

During the project design phase, an EnergyPro model and excel sheet models were developed to simulate the system, including solar fraction, collector efficiency, and heat load of the district heating system. Using 30 years of average historical weather data as a basis, the simulation model predicted that the system would provide more than 95% of the heating energy by solar. The average solar collector efficiency is more than 45.9%.

The system started to run in November 2019, and the performance of the system has been monitored since then by using its automatic control and data acquisition system. In practice, about 75% heating area was running in the 2019-2020 heating season. In the 2020-2021 heating season, 100% of the system was running. Since the system is designed as a high fraction, some collectors should be covered in non-heating months and low heating demand days (mainly in October, April, and May). Figure 4 is the comparison from November to March, which has almost no cover collectors. The average annual collector efficiency is about 47.8% compared with the predicted collector efficiency of 45.9% based on the gross area of the collectors, which means the current calculation method is relatively accurate.



Fig. 4: System production

The actual solar fraction was 100% compared to the predicted 95%. After analyzing the calculation, actual solar radiation is about 10% higher than historical weather data in January and February. Another reason is that the local solar radiation is intense, and there will be some heat going into the house through big windows from 11:00 a.m. to 5:00 p.m. in the daytime. This heat should not be ignored in future designs.

4. Solar field performance

4.1. Collector and Array

Collectors of each gross area are 15.00 m², and apertures of 13.75 m² are applied in the Zhongba project. The efficiency from the supplier is below,

$$\eta = 0.85 - (2.3*(T_m - T_a))/G - (0.029*(T_m - T_a)^2)/G \qquad (eq. 1.1)$$

Harp collectors are chosen for this system and connected in series to form a collector row, while the absorber pipes of each collector are arranged in parallel.



Fig. 5: Collector array schematic diagram

Each row has 60 pcs collectors, where 15 pcs collectors are connected in series, and two series share the same outlet pipes to reduce heat loss and system investment.

A non-Tichelmann connection is applied, and a balance valve from the IMI company combined with adjustments of pipe diameters is designed to reach homogeneous flow distribution (see Figure 3). The valve is calculated by Hyselect and precisely regulated.



Fig. 6: Balance valve and arrangement diagram

4.2. Solar Irradiation

The solar field flow rate is controlled by irradiation in the Zhongba system. Nine solar irradiation sensors are divided into three groups are installed in different positions of solar field to reduce measure deviation. SP214-SS from Apogee company is used and fix in frame of collector.



Fig. 7: Irradiation sensor and arrangement diagram

Zhongba is located at 29.762°N latitude and 84.032°E longitude and adopts GMT+8:00, which causes the sun to rise after ten o'clock and goes down around seven o'clock in winter. Several typical randomly selected kinds of weather are chosen to analyze the irradiation.



Fig. 8: Typical day irradiation in Zhongba (2 min interval)

The radiation value is relatively high, sometimes even exceeding the solar constant. The possible reason is that clouds and mountains bring transient scattering intensity to increase the radiation value. Because the radiation sensor, instead of the radiation meter, is used in this project, measurement accuracy cannot be promised. The reasons should be

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further studied. It also can be found that the local radiation is very unstable, and it is difficult to find a relatively stable period for accurate analysis of the radiation and system performance.

4.3. Sensor Layout

Some sensors and measured parameter values are introduced to analyze the system better.

(1) Irradiation (G): According to the arrangement described in chapter4.1, the average value of nine measured values is usually taken as the radiation value G. If a sensor fails, the system will judge and eliminate the measured value of the faulty sensor. Because irradiation sensor measurement deviation and uncertainty value are relatively large, the controller will correct the irradiation value and flow rate to ensure that the outlet temperature of the solar field reaches the set value.

(2) Collector inlet and outlet temperature (T_{in} , T_{out}): Total of 16pcs sensors with 8 pcs inlet and 8 pcs outlet sensor of type 7403A1A from PR company are applied in the system.

(3) Average collector temperature T_m: The average inlet and outlet temperature

 $T_m = (T_{in} + T_{out})/2$ (eq. 1.2)

(4) Ambient temperature (Ta): Two ambient temperature sensors are installed in the solar field, using type 7403 from the PR company.

(5)Inlet and outlet temperatures of solar field heat exchanger ($Th_{x, in}$, $Th_{x, out}$): The energy from the solar field is passed through the heat exchanger (HX1), the inlet temperature is defined as $Th_{x, in}$, and the outlet temperature is defined as $Th_{x, out}$. Type 7403A1A from the PR company is applied in the system.

(6)Total flow of solar field (q_{sol}) :

In order to better control the flow through irradiation, a flow sensor is installed in the main pipe, which indicates the total flow of the solar field. Type MAG5000+ MAG310P from Siemens is adopted.

(7) System production (P_{pro}):

As the heat collection field of this project uses antifreeze, it is not possible to directly set up a heat meter in the heat collection field. Therefore, a heat meter is installed on the secondary side of the heat collector plate (the medium is water). The heat meter type is Multical 801 from KAMSTRUP company.

4.4. Array Efficiency Analysis Method

At present, there is no unified standard for the testing of collector arrays. Meanwhile, the systems measure mainly depends on the system operation requirements, which means some value cannot get from this system. This paper will apply four different methods to analyze and compare the efficiency of the collector array.

(1) Based on the theoretical efficiency of the collector: Calculated by Equation 1.1, which is defined as $\eta 1$ here.

(2) Based on the heat at the inlet and outlet of the collector: Here is defined as $\eta 2$

 $\eta 2 = c \rho q_v \Delta t_1 / (3.6 GAc)$ (eq. 1.3)

Where

c: Specific heat capacity of propylene glycol, calculated by equation 1.4 [J/kg/°C]

 ρ : Density of propylene glycol, calculated by equation 1.5 [kg/m³]

 q_v : Total circulating flow of heat collecting field [m³/h]

 Δt_1 : The temperature difference between the inlet and outlet of the collector, $\Delta t_1 = T_{out} - T_{in}$ [°C]

G: Solar radiation [W/m²]

Ac: Total area of the heat collecting field, the project is 32,175 m²

The manufacturer generally calculates the specific heat and density of propylene glycol-based on the equation fitted by the measured data. This project uses 45% propylene glycol, and its value at different temperatures is as equations 1.4 and 1.5.

 $c = 3633.48 + 203.59 T_m / 100 + 93.54 T_m / 100 T_m / 100$ (eq. 1.4)

 $\rho = (1045.47-51.91* T_m / 100-16.69* T_m / 100* T_m / 100) \quad (eq. 1.5)$

Where T_m is calculated by Equation 1.2.

(3) Based on the heat of the primary side of the HX1: Here is defined as $\eta 3$

 $\eta_{3} = c \rho q_{v} \Delta t_{2} / (3.6 G A_{c})$ (eq. 1.6)

This calculation method is the same as equation 1.3. The difference is that the temperature difference is taken from the temperature difference between the inlet and outlet of the primary side of the heat exchanger. $\Delta t2=Th_{x,in}-Th_{x,out}$

(4) Based on plate exchange secondary side heat: Here is defined as $\eta 4$

 $\eta 4 = P_{\text{field}} / (G.A_c) \tag{eq. 1.7}$

 η_1 is the theoretical efficiency of the collector, while the project is installed by multiple sets of collectors in series and parallel. The measured value of the theoretical efficiency and the actual collectors' array efficiency has a big difference in irradiation, wind speed, and flow speed. Therefore, the difference between the collector and array efficiency is also an important content of this paper.

 η_2 uses the inlet and outlet temperature directly from the collector array to calculate the efficiency. This temperature value is more suitable for measuring efficiency. However, due to the limited number of temperature sensors in the project, and it is impossible to set the flow sensor at the specific collector array, there may be uneven flow distribution, which may cause deviations in the calculated efficiency. At the same time, the density and specific heat capacity of propylene glycol apply the average temperature and fitted equation. Therefore, the deviation of the efficiency calculation may be further exacerbated.

 η_3 calculates the efficiency using the flow rate and temperature difference of the primary side of the heat exchange (HX1). The measured temperature difference can be considered the comprehensive temperature difference of the entire solar field, but the deviation of propylene glycol's density and specific heat capacity is still unavoidable. At the same time, the measured efficiency is affected by the heat loss of the field pipeline and heat exchanger unit.

 η_4 adopts the heat energy meter's measured value on the secondary side of the heat exchange (HX1). The medium on this side is water, so the calorific value is more accurate. However, the efficiency of the measurement is affected by the loss of the pipeline, the loss in the unit, and the logarithmic temperature difference of the exchanger. This value can reflect the solar field power more accurately, but there is a deviation for the collector array efficiency.

4.5. Collector Array Efficiency

It is impossible to measure and calculate the collector array efficiency accurately based on the current system conditions. Therefore, this paper will compare and analyze different measurement methods, hoping to provide ideas for accurate measurement in the future.

In order to ensure better measurement and analysis, it is necessary to select a period with slight radiation fluctuation and no collector covering. Here is the data from December 1, 2020.



Fig. 9: Comparison of different efficiency (2 min interval)

The corresponding irradiation and the average temperature of the collector are shown in Figure 10.

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Fig. 10: Corresponding irradiation and average temperature (2 min interval)

It can be found that the measured values of η_2 , η_3 , and η_4 are almost the same when the irradiation is high, and they are all higher than the theoretical calculation values η_1 , which reflects the excellent performance of the collector array and small heat losses of pipes and units.

The curves of η_3 and η_4 are the same, reflecting that the logarithmic temperature difference of heat exchange has little effect on the heat collection efficiency, mainly because this project adopts two parallel exchanges operated simultaneously. The designed logarithmic temperature difference temperature is only 3°C.

In the case of high irradiation, the values η_1 , η_2 , η_3 , and η_4 are all greater than 60%, the highest of η_2 , η_3 , and η_4 is even up to 66%, which is greater than expected. It also reflects the possible problems with the current measuring and calculation method of heat collection efficiency. There may be several reasons. First, the project uses an irradiance sensor rather than a highly accurate irradiance meter which will cause the calculation efficiency to be significant. Second. This project uses nine different irradiation sensors to take the average value. The value is not enough to reflect the accurate irradiation of the entire solar field. The calculated efficiency will also be too large if the calculated irradiance value G is smaller than the actual value. Third, the sensors in the project only ensure the system's operation but cannot perform accurate measurements. The errors of sensors will also affect the final value.

After further analysis of the above data, it can be found that when the irradiation intensity is low, the theoretical value is greater than the actual value. This is because of the effect of irradiation on efficiency, and on the other hand, low irradiation occurs in the morning and evening. Furthermore, the theoretical calculation efficiency does not consider the influence of the incident angle on the measured value, which causes deviation. When the radiation intensity is high, the actual measured efficiency is higher than the theoretical efficiency, reflecting the collector's excellent performance under high radiation conditions.

5.Tank performance

5.1. Tank Introduction

The project uses steel tanks as heat storage which also undertakes the supply pressure for the city grid. In this way, installing a heat exchanger on the city gird is unnecessary, which can reduce the temperature loss and improve the collector's efficiency.



Fig. 11: Steel tank and overall dimensions

Steel tanks are adopted as heat storage which also provides city grid pressure. In this way, installing a heat exchanger

on the city gird is unnecessary, which can reduce the temperature loss and collector efficiency.

There are four diffusers in the tank. Diffuser I is connected to solar field supplying and city gird returning. Diffuser II is for the mid-temperature solar system, while Diffuser III is for the high temperature. The diffuser is just simply designed based on the best cost-performance ratio instead of best stratification. Anyhow it shows good performance where temperature difference between top and bottom reach nearly 40° C. Here is the temperature on Dec.1, 2020.



Fig. 12: Steel tank stratification on one day

5.2. Average Heat Loss Factor

Regarding the Chinese standard GB/T 28745-2012, the heat loss factors of steel tanks can be defined as

$$\mathbf{U}_{L} = \frac{\rho_{w}c_{w}}{\Delta\tau} \ln \left[\frac{\sum_{i=1}^{n} t_{i} / n - \sum_{j=1}^{m} t_{j} / m}{\sum_{j=1}^{n} t_{j} / n - \sum_{j=1}^{m} t_{j} / m} \right]$$

(eq. 1.8)

Where

UL: Average heat loss factor [W/m³/K]

ρ: Fluid density [kg/m³]

c: Fluid specific heat capacity [J/kg/°C]

 $\Delta \tau$: Measurement time [s]

t_i: Initial temperature [°C]

n: Number of sensors

 $t_j:$ Average daily ambient temperature [°C], which can be measured and calculated every day.

m: Measurement day time

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t_f: Finished temperature [°C]
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This equation is only applicable to steel tanks whose sensor position is evenly distributed along with the height, and the tank is a cylindrical structure with the same diameter up and down.

During the heating season, the tank will charge and discharge every day and every minute. It is hard to measure and calculated the data. Several days after the system is stopped, the tank temperature can be relatively stable. Here in the table is the data from July 1 to August 7.

Sensor	1-Jul (°C)	7-Aug (°C)	Sensor	1-Jul (°C)	7-Aug (°C)	Sensor	1-Jul (°C)	7-Aug (°C)
TT. S1	52.99	49.36	TT. S9	48.63	49.37	TT. S17	42.72	42.04
TT. S2	52.99	49.38	TT. S10	46.49	46.5	TT. S18	42.51	41.76
TT. S3	52.98	49.35	TT. S11	46.11	45.57	TT. S19	42.1	41.32
TT. S4	52.91	49.24	TT. S12	45.98	45.2	TT. S20	41.2	40.71
TT. S5	52.99	49.41	TT. S13	45.62	44.59	TT. S21	40.92	40.33
TT. S6	52.99	49.35	TT. S14	44.75	43.9	TT. S22	40.73	39.67
TT. S7	52.9	49.31	TT. S15	43.49	42.93	TT. S23	40.71	38.21
TT. S8	50.93	49.3	TT. S16	43.11	42.41	TT. S24	37.72	33.04

Tab. 2: Tank temperature from July 1 to August 7 (S1 is the top sensor, S24 is the bottom sensor)

The ambient temperature is measured in hours. Here is the average everyday temperature, and the total mean temperature from July 1 to August 7 can be calculated, which is 12.26°C.



Fig. 13: The ambient temperature from July 1 to August 7

The average heat loss factor is $U_L=0.0673 \text{ W/m}^3/\text{K}$. We can simulate the system performance by day or by the hour with this data, considering the tank heat loss. U_L is also an essential parameter for steel tank evaluation.

6.PV System Performance

Zhongba has not been connected to the national grid before. Therefore, a 200-kW photovoltaic system working with a 372-kWh battery and a diesel generator is chosen to meet system and domestic electricity demand.

According to data on December 19, 2020, the PV panel started working from around 7:40 and gradually increased. The photovoltaic power was less than the load before 08:30, which brings the battery discharging. After that, the photovoltaic power is greater than the load, and the extra power is supplied to the battery. From 11:10 to 13:30 and after 13:30, a similar phenomenon happens again until 16:30.



Fig. 14: PV system data on December 19, 2020

Here we choose the whole 2020 year. From January to December 2020, the total photovoltaic power generation capacity is 260711 kWh. It can save savings about 181,194 CNY based on Tibet electricity price of 0.695 yuan/kWh, while saves 651,778 CNY if all electricity is supplied from diesel generators, which is about 2.5 yuan/kWh in Zhongba. The PV system return on investment can reach 3-8 years in Zhongba.



Fig. 15: PV system in 2020

In 2020, the average power supply of photovoltaic energy storage systems will account for 74%. The photovoltaic has a high degree of consistency with the solar heating system's power demand, but the battery is still required for regulation if no city power.

7.Conclusion

The system meets the design requirements through the analysis of one year's operation. The solar field and heating load are consistent with the design. The success of this project also proves the feasibility and economic value of a high solar fraction district heating system in cold and high-altitude areas.

Four different methods are given and compared to measure the array efficiency, but the best method is still required in the future. The collector array appears to have good performance and even more than expected, but there may be some error in the measured data, which should be further analyzed.

The heat loss factor is introduced by evaluating the steel tank insulation performance. Maybe a more reasonable index can be applied in the future.

PV system appears to have good performance as expected. PV system can be nearly 100% supply for solar heating system operation if the loaded power is calculated and predicted in more detail, and the battery is well proportioned with PV power,

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Operational Behavior of a Solar-Fed Bidirectional Substation for 4GDH Networks

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Abstract

Decentralized feed-in of solar surplus heat from prosumers into a District Heating Network is here addressed. A specified architecture combining a Return/Supply connection, a set of valves, a feed-in pump and a primary side connection of the solar field led to the conception and fabrication of a bidirectional substation prototype. The latter is tested in a hardware-in-the-loop configuration regarding the consumer and solar field sides while the DHN side of the substation prototype is connected to a real DHN. A 12-days sequence, representative of typical days, with varying solar irradiation, DHN thermo-hydraulic conditions and consumer demands is performed with the prototype. A set of indicators showed i) an inappropriate behavior of the controller during the coldest days, ii) various improvements of the solar fraction during the hottest days (with up to 52% of total solar fraction) and iii) rather good performances of the controller (about 90% effectiveness). The analysis was completed by the observation of detailed dynamic result for one day. Different operating regimes (full DHN consumption, solar self-consumption complemented by the DHN, solar self-consumption and feed-in) could be observed during a single day highlighting the modularity of the BSST to switch automatically (by hydraulic balancing) from one mode to the other.

Keywords: Solar Feed-In, Decentralized, Bidirectional Substation, District Heating,

1. Introduction and State-Of-the-Art

In the "2way District Heating" course of action from the 4th Generation District Heating concept (Lund et al., 2014), decentralized feed-in of solar heat from prosumers seems to be a promising solution to increase the share of renewable energy in District Heating Networks (DHN), especially in dense urban areas with limited ground surface and high cost of land. However, when scattered customers roofs are used to collect and inject heat locally in a network, a new component is required. Such a component, referred here as Bidirectional SubSTation (BSST), must be able to transfer heat i) from the DHN to the local consumer when the locally produced solar heat is not sufficient and ii) from the local consumer to the DHN when solar heat is in excess.

Among the various reinjection principles, Return to Supply (R/S) feed-in is chosen since it seems to be the most flexible option from the DHN point of view (Lennermo and Lauenburg, 2016). Indeed, it allows a reasonably low temperature in the solar field (better panels' efficiency) without increasing the return line temperature (better efficiency of other heat generators and lower heat loss) while presenting lower risks in terms of pipe fatigue. However, R/S feed-in implies the necessity to cope with the variable i) local differential pressure between the return and supply lines, ii) solar irradiation, and iii) local DHN return temperature. Moreover, the feed-in temperature must be close to the local supply line temperature of the network to prevent both pipe fatigue (Lennermo et al., 2019) and unmet customer demand.

While architecture and operational behavior of feed-only substations are addressed in the literature rather extensively (Lennermo et al., 2019; Rosemann et al., 2018; Schäfer and Schmidt, 2016), 2-way substations studies are seldom in the open literature. Though, the combined substation concept of Rosemann et al. (2017) can be noted. Starting from usual feed-only architecture combining a set-of-valves and a feed-in pump on the primary side, they used a rather complex control algorithm and architecture of the substation combining on the secondary side the solar field together with consumer internal heating loops.

© 2021. The Authors. Published by International Solar Energy Society Selection and/or peer review under responsibility of Scientific Committee doi:10.18086/swc.2021.28.03 Available at http://proceedings.ises.org In the frame of the Horizon 2020 THERMOSS project, specifications, modeling and prototype testing of a 2-way substation with the solar field connected on the primary side is performed. While the specifications and modeling approach were presented respectively in Lamaison et al. (2017) and Lamaison et al. (2018), the present paper deals with the design and original test approach of a BSST prototype combining hardware-in-the-loop and real experimental DHN.

2. Architecture and Control

2.1. Architecture

To build the BSST architecture, an initial review on two-way substation both from the industrial and research point of view led to the fact that i) nothing exists in the catalogue of usual manufacturers; ii) the Return/Supply (R/S) type of feed-in is the most promising compared to other types (R/R or S/S).

Discussions with DHN operator and substation manufacturer led to specifications in the form of constraints and requirements, insisting specifically on modularity and cost. Different features (local usage, network connection and control strategy) were then combined to propose various architectures. After pros and cons listing, solutions involving complete reinjection of the heat into the DHN seemed the most promising (Lamaison et al., 2017), leading to the technical drawing shown in Fig. 1. Especially, the substation does not include a storage as usually associated to a solar field. Indeed, thanks to the presence of the DHN as heat sink and because of the extra heat loss induced by a storage, it is not necessary and thus preferred not to include a storage in the architecture

In Fig. 1, connections to the supply and return lines of the DHN are schematically represented on the left block. Regarding the right block, it represents the consumer and exhibits a separation of space heating (SH) and domestic hot water (DHW) supplies at the primary side (dedicated heat exchangers) Regarding the middle block, it is comprised of the connection to the solar loop and the entire feed-in loop components. For the latter, the main components are the feed-in pump (P_SST_FEED), the heat exchanger (ECH_BESST_SOL) and the feed-in valve (V_BSST_FEED). Red and blue lines respectively indicate hot and cold lines. Red, blue, orange and black labels respectively denote temperature probes, pressure probes, mass flow meters and equipment. The main equipment (pumps, heat exchangers and valves), small hydraulic components (filters, check valves) and the instrumentations are highlighted. Also, it is important to mention that drains (all loops), safety valves (all loops) and expansion tanks (solar and SH loops) are not shown.



Fig. 1: Technical drawing of the BSST prototype

2.2. Main principles and control

The two main operating modes of the substation are schematically represented in Fig. 2:

• In mode 1, the heat consumption for domestic hot water and space heating is larger than the solar production. The solar energy if any is used for the consumer needs in addition to the heat coming from the network. The flow in the service lines is thus from the supply to the return line;

• In mode 2, the heat consumption is lower than the solar production. The solar energy is used to entirely satisfy the consumer needs if any and the surplus heat is reinjected to the network. The flow in the service lines is thus from the return to the supply line.



Fig. 2: Main operating principles

Regarding the substation control, the solar field pump (P_BSST_SOL) is controlled to obtain a given flow rate set point. Similarly to Lennermo et al. (2019), the latter is calculated using a cascaded combination of a theoretical solar field model (function of solar irradiation, return temperature TT_BSST_11 and ambient temperature) and a closed-loop PID leading to a desired set point for the outlet solar field temperature (TT_BSST_10). For the latter set point, an adapted heating law as a function of the ambient temperature is implemented. The feed-in pump (P_BSST_FEED) is controlled to have the same flow-rate as in the solar loop (accounting for the calorific value correction between the glycol on the solar loop and the water in the BSST loop). The extra set of valves (V_BSST_BP1 and V_BSST_BP2) are used for specific transient conditions. Based on the demand side and solar production, the flow rate will automatically be distributed, due to hydraulic balancing, such as in mode 1 or mode 2.

3. Sizing, test setup and procedure

3.1 Sizing

Following a stage of modeling (Lamaison et al., 2018), the substation has been sized (heat exchangers, valves and pumps) for 42 kW in SH, 60kW in DHW and 70kW in solar. According to the sizing and architecture, the substation has been assembled as shown in Fig. 3.



Fig. 3: Picture of the bidirectional substation with some components of Fig. 1 highlighted

3.2 Testing setup and procedure

In the frame of the project, different types of tests were performed:

- Unitary tests: Validation of the functional control of the different blocks;
- Real weather conditions: Operation of the substation with a real solar field;
- **Real time emulated weather conditions**: Operation of the substation in a broader range of operating conditions but with an emulated solar field.

For the present work, only the emulated weather conditions tests are presented. For those tests, a dynamic whole system methodology, called SCSPT (Short Cycle System Performance Test) and adapted from Albaric et al. (2008), is used. As shown in Fig. 4, it consists in real-time hardware in the loop (HIL) dynamic system test for thermal systems during 12 days. It relies on TRNSYS dynamic simulation system to cover the typical working conditions during 12 months of operation. The simulation calculates real time needs (building) and production (solar field). These are then sent to a Labview program, which sent the required info to various thermo-hydraulic modules, composed of heat exchangers, valves, pumps and electrical resistances, which translate the theoretical needs in real thermo-hydraulic fluxes. The test conditions are here representative of annual variations of the Zurich climate (CH).



Fig. 4: Dynamic whole system test methodology

The entire setup for testing the substation is finally as shown in Fig. 5 with the BSST prototype surrounded by different components.

- The emulated building space heating (SH): The building model is a typical 4 levels building erected in the early 2000's in France, parallelepiped U-shape, convex side facing south. It is composed of 12 apartments, each heated according to its thermal zone temperature by local radiator flow rate adjustment with thermostatic valve. The space heating flow is a constant value (local bypass at radiator level when thermostatic valve adjust the flow rate in radiator).
- The emulated building domestic hot water (DHW) and sanitary loop: The DHW model consists in a repeated daily pattern draw-offs profile for 12 households (obtained using Jordan and Vajen, 2005), with total daily consumption variation from month to month. The DHW sanitary loop demand is not calculated from simulation but rather physically emulated. To do so, a specific hydraulic module for real heat dissipation to ambient temperature was built. The water flow rate in the loop is fixed to 300kg/h by recycling pump and the heat dissipation is controlled dynamically to keep the inlet-outlet temperature drop close to 5K.
- The emulated solar field: The modeled solar field is facing south and is composed of 50 m² of common technology flat solar panel. It is worth mentioning here that the size of this solar field is limited by the capacity of the hardward-in-the-loop setup. In theory and as discussed in Lamaison et al. (2018), the size of the solar field can be larger when associated to such substation.
- The real DHN: Unlike the building and solar field sides that are emulated, the DHN side is connected

to a small real DHN with varying local differential pressure and return temperature conditions. It is composed of a district heating network of about 200m length, supplying heat to real buildings and to an emulated building (the one in which the BSST is connected). The main production units of this DHN are a condensing gas boiler of 280kW, a heat pump of 50kW and a solar field of 300m². The network is also equipped with a hot storage tank of 40m³.



Fig. 5: BSST test setup at CEA-INES: emulated building, emulated solar field and real DHN

4. Results and discussion

The results are firstly presented globally for each day of the test sequence using indicators and secondly with the analysis of the dynamic behavior for a specific day of operation.

4.1. Indicators definition and results for the 12-days sequence

Using the nomenclature of both Fig. 1 and Fig. 6, Tab. 1 and Tab. 2 respectively present the definition of a set of energy-based and control-based indicators. While the former objective is to illustrate the energetic performances of the substation, the latter one is to present the controller performances in feed-in mode.



Fig. 6: Schematic representation and nomenclature associated to thermal power fluxes (Q) around the substation

Tab. 1: Energ	gy (E) base	d indicators	definition
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Name	Definition	Description		
Solar Field Efficiency	$\eta_{SF} = \frac{E_{solar, field}}{E_{solar, irr}}$	Collected energy at the panels level divided by global irradiation on the solar panels plan		
Solar Plant Efficiency	$\eta_{SP} = \frac{E_{solar,coll}}{E_{solar,irr}}$	Collected energy at the solar heat exchanger divided by global irradiation on the solar panels plan		
Substation Efficiency	$\eta_{th} = \frac{E_{SST,feed-in} + E_{SH} + E_{DHW}}{E_{solar,coll} + E_{SST,cons}}$	Total distributed energy by the SST divided by total collected energy by the SST		
Solar Fraction	$SF = \frac{E_{SH} + E_{DHW} - E_{SST,cons}}{E_{SH} + E_{DHW}}$	Solar energy self-consumption by building divided by total building consumption		
Total Solar Fraction	$SF_{tot} = \frac{E_{SST, feed-in} + E_{SH} + E_{DHW} - E_{SST, cons}}{E_{SH} + E_{DHW}}$	Solar energy self-consumption and reinjection divided by total building consumption		
Solar Ressource Feed-in Rate	$\tau_{feed} = \frac{E_{SST, feed-in}}{E_{solar, coll}}$	Feed-in energy divided by collected energy at the solar heat exchanger		
Substation Prosumer Rate	$\tau_{\rm pro} = \frac{E_{\rm SST,feed-in}}{E_{\rm SST,cons} + E_{\rm SST,feed-in}}$	Feed-in energy divided by the summed fluxes at the entrance of the SST on the DHN side		
Substation Prosumer Rate with respect to DHN	$\tau_{\text{pro,DHN}} = \frac{E_{\text{SST,feed-in}}}{E_{\text{SST,DHN}} + E_{\text{SST,feed-in}}}$	Locally feed-in energy divided by summed fluxes at the entrance of all the SST of the entire DHN		

Tab. 2: Control-based indicators definition

Name	Definition	Description
Standard Deviation of the Feed-in Temperature	$\sigma_{\text{feed-in}} = \sqrt{\frac{\sum (\text{TT01} - \text{T}_{\text{TT01,mean}})^2 \big _{\text{FBSST}_{\text{DHN}} < 0}}{N_{\text{points}}}}$	When reinjection occurs, standard deviation of the hot line temperature with respect to the reinjection setpoint
Feed-In effectiveness at 2K	$\varepsilon_{\text{feed}-\text{in},\text{E},2\text{K}} = \frac{\sum P_{\text{feed},\text{in}} \Delta t \big _{\text{F}_{\text{BSST}_{\text{DHN}} < 0 \& \text{TT}01 > \text{T}_{\text{sp},\text{TT}01} - 2\text{K}}}{\sum P_{\text{feed},\text{in}} \Delta t \big _{\text{F}_{\text{BSST}_{\text{DHN}} < 0}}}$	When reinjection occurs, energy-based integral when setpoint is satisfied within a 2K margin divided by the total energy-based integral

With the indicators described beforehand, Tab. 3 now presents those for the 12-days sequence of our testing procedure, as described in Section 3. The main conclusions to draw from this Table are the following:

- During the 6 colder days, the solar field does not produce. This is explained by the too high outlet solar field set point constrained by the reinjection arrangement. Indeed, the controller setpoint calculation is based on the assumption that reinjection may occur and is thus rather high because the network operates at high temperature (an average of 75°C for these 6 days). The latter combined with the low irradiation and the low temperature in the solar loop piping (because of the low ambient temperature) leads to an inappropriate solar field operation.
- During the 6 days for which solar reinjection takes place, we observe various levels of solar fraction but more striking various level of total solar fraction. The latter is due to the increased gap for hotter days between the local demand of the building and the energy produced by the solar field. It is worth noting here that the largest value of total solar fraction of 52.0% is still not that high. The reason is the rather small size of the emulated solar field because of test bench limitations (see Section 3). Additional tests not shown here were performed with real solar field of 70kW and solar fractions up to 80% were reached.
- Regarding the performances of the controller, the standard deviation of the feed-in temperature is rather high compared to what was expected from previous tests with a real solar field (see Section 3), for which values around 1.5°C were obtained. These results are explained by the fact that the controller parameters were calibrated with this real solar field and not refreshed after the switch to an emulated solar field (with lower aperture area and less inertia). However, the feed-in effectiveness exhibits reasonably good values (average of 92%) highlighting the fact that reinjection on the network occurs at an appropriate level of temperature.

Day	η_{SF}	η_{SP}	η_{th}	SF	SF _{tot}	τ _{feed}	τ _{pro}	τ _{pro,DHN}	$\sigma_{feed-in}$	€ _{feed−in,E,2K}
1	0	0	98.2	0	0	0	0	0	-	-
2	0	0	98.3	0	0	0	0	0	-	-
3	0	0	98.4	0	0	0	0	0	-	-
4	21.4	20.5	98.6	4.3	4.7	6.0	0.4	0.1	5.6	91.7
5	18.4	17.6	98.8	4.8	6.0	16.2	1.21	0.3	5.8	85.0
6	34.8	33.4	99.7	18.7	25.5	26.3	7.7	2.5	4.0	98.7
7	35.8	34.3	99.6	20.1	33.4	39.3	14.3	1.9	4.0	92.1
8	36.0	34.6	99.9	14.9	52.0	71.1	30.4	4.0	3.7	90.5
9	33.1	31.7	99.4	11.9	32.8	62.1	19.1	2.9	4.1	96.3
10	0	0	97.6	0	0	0	0	0	-	-
11	0	0	98.2	0	0	0	0	0	-	-
12	0	0	98.3	0	0	0	0	0	-	-

Tab. 3: Indicators for the 12-days test sequence

4.3. Focus on dynamic results for a specific day

In the present section, we observe the detailed dynamic results for day $n^{\circ}6$ of the sequence with the indicators results being highlighted in Tab. 3.

Fig. 7 presents thus results obtained for day $n^{\circ}6$ of the sequence between 9a.m. and 7p.m. in terms of various heat transfer rates and temperatures. Fig. 8 presents additional results for the same observation period in terms of heat power at DHN level, controller actuators signals and differential pressures.

Focusing on regions A, B and C highlighted in the Figure, we observe the following operating regimes:

• **Region A**: The BSST is in consumption mode from the DHN point of view (mode 1 in Fig. 2). The outlet solar loop temperature and thus the outlet feed-in loop temperatures are below the feed-in set point. The feed-in pump is off and the solar pump operates at its lowest speed. The building consumption is thus entirely met by the DH and TT01 at the entrance of the substation on the hot service line is representative of the DHN local supply pipe temperature. The local differential pressure, here imposed by the DHN pump, is following the local building consumption indicating that i) there is no local consumption of solar heat, and ii) the other consumer on the network have a rather constant heat consumption (see top graph of Fig. 7).

- **Region B**: The BSST is in consumption mode from the DHN point of view (mode 1 in Fig. 2). However, periodically, the SST consumption is lower than the building consumption indicating solar heat production and self-consumption. This is the case especially at the end of the period where the outlet solar field temperature surpasses the feed-in set point. This self-consumption is achieved in a period where the substation consumption is significantly varying because of DHW draw-offs (see DHW valve opening in Fig. 8). The latter variations together with the variable solar fraction lead to large variations of the local differential pressure drop (imposed by the DHN pump) indicating strong flow rate variations in the DHN.
- **Region C:** The substation is in feed-in mode from the DHN point of view (mode 2 in Fig. 2). The solar heat being used for both the local building heat demand and for reinjection into the DHN. The feed-in pump is ON and the valve V_BSST_FEED together with the pump speed are adjusted to match the flow rate set point. TT09 at the entrance of the substation on the cold service line is representative of the DHN local return pipe temperature. Because of feed-in mode operation, the differential pressure is here imposed by the feed-in pump. Its variations are following the variations in demand of the other DHN consumers (see top graph on Fig. 7).

The main negative observation that can be made here for this day of operation is the low frequency periodic alternation between consumption and feed-in modes even though solar irradiation and building consumption do not exhibit such behaviors. The latter is attributed to controller setting slightly inappropriate since they were established during tests with a real solar field (with larger aperture area and more inertia) and not refreshed for this new testing setup.



Fig. 7: Experimental results obtained for day 6 of the sequence (Top: heat power; Bottom: Temperatures)



Fig. 8: Experimental results obtained for day 6 of the sequence (Top: heat power at DHN level; Middle: Controller actuators, Bottom: Differential Pressure)

A very interesting insight offered by our testing setup is the observation of the DHN pressure field variations because of the reinjection. Indeed, because of the usage of a real network, furthermore linear, influence on the DHN pressure cone is directly visible. As shown in Fig. 9, which presents a qualitative explanation of the influence of the feed-in on the real DHN pressure cone, the solar heat produced at prosumer 1 benefits both the local consumer (consumer 3 = prosumer 1, cf. top graph on Fig. 7) and consumer 2, which thus reduces its dependence to the main production plant.

It is worth mentioning here that during tests with extreme conditions (larger solar field, low demand on the network), we reached situations with a fully inverted pressure cone which becomes problematic if no bypass for backflow is installed in the main plant (as mentioned in Heymann and Rühling, 2016).



Fig. 9: Qualitative impact of the BSST on the real DHN pressure cone

5. Conclusion

The present paper presented the operational behavior of a new prototype of a solar-fed bidirectional substation. This represents the final step of the THERMOSS project in which specifications, modeling, sizing, manufacturing and testing of such a prototype was performed. The prototype was sized for about 100kW in consumption and 70kW in production and can be considered in a first approach as a superposition of a consumption substation (with primary separation between DHW and SH) and a solar-fed feed-in substation.

The testing setup was composed of i) an emulated building SH and DHW consumption (real-time TRNSYS simulation associated to a Labview program and a set of thermo-hydraulic modules), ii) an emulated solar field (real-time TRNSYS simulation associated to a Labview program and a thermo-hydraulic module), and iii) a real 200m long linear DHN. The testing was performed during 12 days representative in terms of boundary conditions of the 12 months of the year.

A set of indicators showed i) an inappropriate behavior of the controller during the coldest days, ii) various improvements of the solar fraction during the hottest days (with up to 52% of total solar fraction) and iii) rather good performances of the controller. The analysis was complemented by the observation of detailed dynamic result for one day of the sequence. Different operating regimes (full DHN consumption, solar self-consumption complemented by the DHN, solar self-consumption and feed-in) could be observed during a single day highlighting the modularity of the BSST to switch automatically (by hydraulic balancing) from one mode to the other. Unwanted low frequency oscillations between the modes were also observed.

As a conclusion, we can say that the experimental results shown here represent a satisfactory first step for such a bidirectional substation. However, there exists still some room for improvements regarding the control, especially by benefiting from the local consumer information to adapt the control of the feed-in loop. This is currently under investigation.

6. Acknowledgments

The project THERMOSS has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 723562.

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I-03. Heat for Industrial and Agricultural Processes
Renewable Thermal Energy Systems Designed for Industrial Process Solutions in Multiple Industries

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Abstract

Industrial decarbonization can and must be accelerated by removing fossil fuels from the provision of process heat. Doing so at temperatures less than 250°C which accounts for about 2/3 of industrial process heat (IPH) but is not receiving the attention of areas such as steel and cement, is a particularly promising opportunity. This paper looks at the results of two case studies for understanding the economics and potential for renewable thermal energy systems (RTES) in hybrid configurations to provide IPH. The first case study looks at using district heat as an input for a heat pump--three cases were run harvesting energy from ambient water (5°C), sewage water (20°C), and a solar collector (35°C). The second case study looks at the use of linear Fresnel collectors (LFCs) coupled with phase change material (PCM) thermal energy storage (TES) for direct steam generation (DSG). Accounting for elevated costs of infrastructure for each heat source, the levelized cost of heat (LCOH) of the first case study ranged from \$4-\$10 per million British Thermal Units (MMBTU). For the second case study modeling LFCs with PCM and TES, the results show that a LCOH of \$9-\$15 per MMBTU is possible, depending on the direct normal irradiance.

Keywords: SIPH, RTES, CST, DSG, heat pumps, LCOH, Industrial Decarbonization, TEA

1. Background

The need for renewable heat in industry is vital for the next decade and beyond. Global industrial heating applications are estimated to be approximately 20% of the total global energy consumed (IRENA, 2019). This energy is overwhelming supplied by the burning of fossil fuels, principally coal and natural gas, to produce the heat or steam. As the world looks to decrease emissions, industrial decarbonization and the reduction of fossil fuels through renewable alternatives is becoming an increasingly important topic but has been under-researched. Recent work from the National Renewable Energy Laboratory (NREL) found that significant opportunity for solar industrial process heat (SIPH) exists in the United States. Estimates indicate that nearly 2/3 of the industrial thermal demand in 2014 in the United States is less than 250°C, which is ideally suited to solar and renewable heat systems (McMillan et al., 2021). Concentrating solar thermal (CST), photovoltaic (PV), and grid coupled heat pumps can be considered in stand-alone or hybrid configurations (e.g., where multiple technology options couple to provide temperatures at different levels) of renewable thermal energy systems (RTES). Such systems can provide low to medium temperature heat less than 250°C (Akar et al., 2021), but need costs to decrease to increase deployment. Two areas examined in this paper are district heating and food/beverage processing.

District heating is a strong candidate for heat pump application, as heat pumps are already used extensively in space heating. For an effective district heating system, the distributed water or steam should be elevated to temperatures ranging from 50°C-100°C for hot water, and above 110°C for steam systems (Nielsen and Sørensen, 2016; Thorsteinsson, 2008). Heat pumps currently provide district heating with aggregated thermal capacity of 1.58 GW across 11 European countries (David et al., 2017). The U.S. has considerably lower deployment of heat pumps though it does have an estimated 1.5 GW of operational district heating systems which utilize hot water for campuses and cities. These systems could potentially benefit from heat pump augmentation (EIA, 2018).

Dairy and food processing sites have been repeatedly found theoretically and practically suitable for stand-alone RTES use. The steam and heat needs can be readily supplied by RTES, such as CST for animal food processing and dairies (Kurup and Turchi, 2015). For example, in Switzerland, an operating parabolic trough system uses water-glycol which provides heat for the milk processing (Kurup et al., 2017). Recently in the United States, CST systems where hot water and steam are produced have been installed at a New York farm and a California dairy processing facility (Skyven Technologies, 2020, 2019). Prior work has also identified breweries as potentially viable for renewable heat, for example when a stand-alone RTES provides heat for the process (Kurup and Turchi, 2020).

2. Introduction

A simplified framework for RTES selection and heat provision (at the overall site level) has been developed (Akar et al., 2021). To better understand commercially viable near-term hybrid RTES solutions, specific hybrid RTES generation code modules or tools were built based on the framework (Akar et al., 2021), and initial results were highlighted in a following paper(Kurup et al., 2021). Those results were to understand the heat generation (i.e., technological performance) from these hybrid RTES models and were not applied to specific end-use cases.

This paper highlights the application of the hybrid RTES framework and newly developed code modules for specific case studies. The models and results explore the techno-economic analysis (TEA) and potential of stand-alone and hybrid RTES applied to potential district heating and food processing applications. Two main case studies are explored in detail. The first case study focuses on high-temperature heat pumps (HTHPs) for district heating and the variables that influence their economics. The second case study uses linear Fresnel collectors (LFCs) for direct steam generation (DSG) coupled with a phase change material (PCM) thermal energy storage (TES) system for food/beverage processing application. This paper builds upon work and the opportunities identified for SIPH in the U.S. (McMillan et al., 2021), and looks to focus it on specific industries of interest and high economic potential. The results for both case studies highlight the levelized cost of heat (LCOH) for different RTES options in meeting the district heating or industrial load.

In parallel with these RTES analyses, an HTHP model has been developed to characterize the opportunity for waste heat valorization in industries with suitable temperature requirements ($90 - 150^{\circ}$ C). The python-based model produces LCOH and economic outputs (e.g., payback period, internal rate of return) based on a given industrial process and technology characteristics such as compressor-type and refrigerants. This model has been used to investigate the economic potential of HTHPs in the dairy and brewing industry, and, for the purposes of this paper, will be used for assessing district heating applications.

HTHPs move heat rather than generate it. Taking advantage of waste heat streams, heat pumps can output more thermal energy than their input in electrical energy, allowing them to potentially improve energy efficiency while reducing the carbon intensity of heat provision. Their combination of increased efficiency, cost savings, and emissions reductions make HTHPs a promising component of industrial electrification. HTHPs are not a new technology, though a global focus on industrial decarbonization has brought renewed interest in how they might contribute to the reduction of fossil fuel use to meet IPH demands. HTHPs up to 90°C have been commercially available since the 1980s, but in the past decade have seen increased interest and an increased number of commercially available models. Though it is technologically possible (as some pilot projects have demonstrated) to lift temperatures up to 150°C and theoretically beyond (Zühlsdorf et al., 2019). The case study presented here will examine the techno-economic potential for HTHPs to supply heat for district-level systems in the United States, a relatively untapped market for these promising technologies. Europe has a history of using HTHPs for various industrial processes, but countries have found them particularly suitable for serving district heating systems (Neves and Mathiesen, 2018). Globally as of 2018 there were more than 20 heat pump models available from 13 identified manufacturers (Arpagaus and Bertsch, 2020). The analysis will evaluate the LCOH of an HTHP for district heating and variables that affect its overall cost of heat delivery. Although this is a U.S. focused case study, it has relevance to other energy markets with a low ratio of natural gas to electricity prices—a challenging energy price environment for heat pump economics. It is worth noting that heat pumps become increasingly competitive as the ratio of natural gas to electricity prices increases.

The second case study uses LFC-DSG coupled with PCM-TES to improve the system's flexibility and capacity factor. The LFC-DSG system is modelled with the System Advisor Model (SAM) which evaluates the annual performance of the solar system. PCMs are chosen as the storage medium as they have relatively high energy densities. Sodium formate has been selected as the storage medium, which has a melting temperature of 258°C. PCMs store energy in the latent heat of the phase change and can be used to produce steam at the phase change temperature, which improves the effectiveness of heat transfer (Sharan et al., 2019). The LFC- DSG system must generate steam at a higher temperature than this so that the steam produced melts the PCM. In this example, the LFC-DSG system designed to produce steam at 5 bar, 270°C and a steam quality of 75%. The steam properties (temperature, mass flow rate, and steam quality) are calculated hourly for the year depending on the available solar resource. The annual performance of the model has been validated with an operating solar field (Kurup et al., 2017).

3. Case study results

3.1. Case Study 1: Standalone HTHP System for District Heating up to 90°C

The case study presented here investigates HTHPs in district heating applications. District heating systems utilize hot water or steam to provide thermal services from a central energy plant to cities, communities, or campuses in a simple and efficient manner. Heat pump driven district heating, while largely unpracticed in the U.S., has been deployed to serve a wider array of European cities over the past 40 years, particularly in Scandinavian regions (Jakobs and Stadtlander, 2020). This disparity can be attributed to past European electrification initiatives, greater general familiarity of heat pump systems in European markets, and European industrial policy that provides greater security for firms, all of which fosters a greater appetite for risk and encourages centralized utilities for shared infrastructure like district heating systems, and established expertise in district heating systems (Werner, 2017).

A model was developed to simulate the performance of HTHPs based on published methodologies (Arpagaus et al., 2018; Bergamini et al., 2019; Kosmadakis et al., 2020) This model was used to assesses the technical performance and economic implications of heat pump-driven district heating in a variety of common scenarios informed by operating conditions of existing European plants and adapted to U.S. energy prices.

In European heat pump-driven district heating systems, the most common sources of waste heat are sewage water, ambient water, and industrial waste heat. To model how HTHPs would perform district heating functions using the listed waste heat sources and in combination with solar technologies, this analysis considered three different source temperatures: 5°C, to represent ambient water sources; 20°C, to represent both sewage water and ground source geothermal sources; and 35°C, to represent both solar thermal preheating systems and industrial waste heat sources. When solar preheaters were used, an elevated capital cost was also assumed to account for the additional expense of the solar thermal collectors. The typical capacity of such district heating configurations ranges between 2-20 MW (David et al., 2017).

Heat pump-driven district heating systems in Europe deliver hot water between 60°C and 90°C (David et al., 2017). It is also a goal of future district heating systems to reduce needed temperatures to 50°C as lower temperatures reduce energy lost to the ambient environment and increase system efficiency (Averfalk and Werner, 2018; Buffa et al., 2019), so this analysis included heat sink temperatures between 50°C and 90°C, in ten-degree increments, to examine how heat pumps would perform across this range. The model used in this analysis can select an optimal refrigerant from a library of over 30 options based on maximum temperature and temperature lift. Because the vast majority of operating heat pump-driven district heating systems in Europe use either R134a or ammonia as refrigerants (David et al., 2017), and R134a is widely being phased out due to its global warming potential, this analysis uses a test case with ammonia as the refrigerant for all scenarios, as well as a test case allowing the model to choose a refrigerant.

The study produced LCOH values for heat pump systems in different configurations and was done parametrically to examine the effects of heat pump performance on the final system economics. The basic heat pump system examined using waste heat at a range of reasonable temperature from 5°C to 35°C to provide hot water from 50°C to 90°C. Using the methodology as described in Kosmadakis and provided in eq. 1-5, ammonia was used as a heat pump refrigerant and a resulting coefficient of performance (COP) of the heat pump was calculated based on refrigerant physical properties, compression ratio of the refrigerant (PR), compression efficiency (ε_{PR}), compressor isentropic efficiency (ε_{is}), and overall compressor efficiency (ε), (Kosmadakis et al., 2020). Kosmadakis et al., suggest ε_{is} values of 60-70% for a two-stage system, this study uses a slightly higher default ε_{is} (75%) to compensate for the lower output temperature range. For the 70°C-80°C delivery temperatures, the refrigerant-based COP was validated against real-world data as reported by European heat pump operators in the range of 3.5-4.0 (David et al., 2017).

$$COP_{Real} = \frac{Q_h}{\dot{W}_c} \tag{eq. 1}$$

$\varepsilon_{is} \in [0.2, 0.95]$ and	$\varepsilon_{is} = 0.75$ by default	(eq. 2)
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 $\varepsilon_{PR} = 0.95 - 0.125 \times PR \tag{eq. 3}$

 $\varepsilon = \varepsilon_{is} \cdot \varepsilon_{PR} \tag{eq. 4}$

$$COP_{Refrigerant-Estimate} = \frac{\varepsilon_{is}\varepsilon_{PR}(h_3-h_2)}{(h_2-h_1)} \approx \frac{\dot{Q}_h}{\dot{W}_c}$$
(eq. 5)

Heat pump capital expenditure (CAPEX) and energy costs significantly affect heat pump economics. For the CAPEX

of heat pumps, low-cost (\$150/kW) and high-cost (\$300/kW) scenarios were evaluated which are based on the maximum per kW electricity drawn by the heat pump system and are conservatively consistent with literature reports of HTHP capital costs (Kosmadakis et al., 2020; Meyers et al., 2018). However, in the case of the combined solar thermal flat plate collector (FPC) and heat pump it was assumed that additional capital costs increased the cost of the combined system to \$700/kW (low-cost) or \$850/kW (high cost) to include both the solar thermal collectors and thermal energy storage. In both situations, a low cost heat pump (\$150/kW) was assumed, with a low and high FPC cost of \$550/kW and \$700/kW (IRENA, 2021). The FPC unit cost is estimated to be between \$400/m² and \$600/m² with no assumed interconnection costs (NREL, 2021). Future analysis should include additional work on the price breakdown of these components when hybridized and additional characterization of a hybrid system's operational requirements. It was also assumed that the electricity procured by a municipality would be relatively low-cost and on the order of \$0.05/kWh, (note: this figure incorporates an estimate of total demand charges amortized into the \$/kWh estimate). Tab. 1 summarizes these inputs to the heat pump model. For all cases, the high temperature output of the heat pump was estimated at 50°C, 60°C, 70°C, 80°C, and 90°C.

Unlike natural gas boiler systems, in which costs are mostly associated with fuel, the majority of costs in heat pump systems are capital costs. This means that a heat pump increases its value and lowers its LCOH at higher capacity factors. The capacity factor (CF) is calculated as the thermal output of the heat pump over a year divided by the maximum potential thermal output for a year as given in eq. 6.

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CF = \frac{Annual Heat Pump Thermal Output (MWh)}{Heat Pump Thermal Capacity (MW) \times 8760 hours} (eq. 6)
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In the cases presented below, the heat pump was assumed to have a CF of 0.3, operating approximately 2600 hours out of the year; this was based on milder climates (EIA, 2021a). In colder climates with longer heating days, or in systems where thermal energy is always used (such as in campus settings where steam systems are always needed), this CF could increase, which would in turn increase the competitiveness of the heat pump system. A subset of cases was re-run with a capacity factor equal to 1 (unrealistic but used as an upper-bound) and the LCOH showed a 10%-30% reduction, meaning the adoption value proposition of heat pumps could be strong in environments with higher and more consistent heating demand, though are likely bound by a 30% reduction from values shown.

Heat Source	Cost Type	Waste Heat Temperature	Capital Cost	Temperatures	
Ambient Water	Low Cost	5°C	\$150/kW		
Amolent water	High Cost	5.0	\$300/kW	50°C, 60°C, 70°C, 80°C, 90°C	
S	Low Cost	2000	\$150/kW		
Sewage	High Cost	20°C	\$300/kW		
Solar Collector -	Low Cost	\$700/kW			
FPC	High Cost	35°C	\$850/kW		

Tab. 1: Capital costs and operating temperature ranges for heat pumps.

The results in Tab. 2 show, as would be expected, that the worst-performing heat pumps use the lowest temperature source (ambient water) and the best-performing use the highest temperature heat source (solar FPC). However, this is an expected result given the thermodynamic principles that govern heat pump COP. The purpose of the analysis is to help understand the trade-off between waste-heat upgrades and resulting LCOH. Because some waste heat sources demand significant additional CAPEX, the case with the best-performing heat pump system does not necessarily achieve the lowest LCOH. OPEX discrepancies are not considered in these calculations.

Tab. 2: Resulting COP from the heat pump model based on available waste temperature

	СОР				
	50°C	60°C	70°C	80°C	90°
Ambient Water	4.50	3.74	3.19	2.78	2.45
Sewage	6.92	5.30	4.31	3.65	3.17
Solar Collector - FPC	14.02	8.62	6.30	5.00	4.16

		LCOH (\$/MMBTU)					
	50°C	60°C	70°C	80°C	90°		
Ambient Water -Low Cost	\$4.56	\$5.29	\$6.03	\$6.76	\$7.53		
Ambient Water -High Cost	\$5.63	\$6.35	\$7.08	\$7.81	\$8.58		
Sewage – Low Cost	\$3.35	\$4.05	\$4.73	\$5.40	\$6.06		
Sewage – High Cost	\$4.40	\$5.10	\$5.79	\$6.45	\$7.11		
Solar Collector FPC – Low Cost	\$6.05	\$6.76	\$7.44	\$8.09	\$8.73		
Solar Collector FPC – High Cost	\$7.10	\$7.81	\$8.49	\$9.14	\$9.78		

Tab. 3: Resulting LCOH for temperature and cases

From the data shown in Tab. 3, the lowest cost/best value LCOH was the system that used sewage waste heat as an input to the heat pump. This was true even when comparing high-cost sewage and low-cost ambient scenarios, which is useful as coupling a heat pump to a sewage plant would likely be a higher capital cost. In the case of installing a solar collector to provide input heat, additional capital costs increased the LCOH of this system's heat above that of the ambient water heat pump system's, meaning that the solar collector/heat pump system is not the most economic option for the cases and cost assumptions examined here (Fig. 1) especially in mild climates.



Fig. 1: LCOH for different types of heat pumps and the delivered heat of the scenarios.

3.2. Case Study 2: RTES in Food / Beverage Processing up to $270^\circ C$

This case study is designed for medium temperature ($\sim 270^{\circ}$ C) industrial heat applications for food/beverage processing facilities such as dairies, breweries or distilleries that use steam for their processes. The case study uses an LFC-DSG coupled with PCM-TES and a natural gas boiler back-up system to improve the system's flexibility and CF. Note this is for a greenfield site, and a backup natural gas system therefore would be needed to guarantee meeting the industrial load. The LFC-DSG system is designed for a 1-megawatt thermal (MW_{th}) capacity with a solar multiple of 2 and target steam quality of 0.75 and modelled in SAM (Fig. 2). For this modeling effort, SAM 2020.11.29 has been used (NREL, 2021). The base case for the hybrid system is a solar multiple of 2 (\sim 3,600 m² of LFC solar field) and 6 hours of PCM thermal storage. Alternative cases for parametric analysis are adjusted for 6-12 hours of storage with a solar multiple between 1.5 (\sim 2,700 m²) and 2.5 (\sim 4,500 m²).

PCMs store energy in the latent heat of the phase change and so are well suited for integration with systems that use steam as the working fluid since both media go through a phase change allowing the temperature profiles to be matched which improves the effectiveness of heat transfer (Sharan et al., 2019) In this case study, sodium formate is selected as the PCM for the TES with 6 hours storage capacity for the base case, due to low-cost (\$0.40/kg). Sodium formate has a melting temperature of 258°C, latent heat of 245 kJ/kg, and heat capacity of 1.2 kJ/kg-K (Sharan et al., 2019).



Fig. 2: Schematic for the base case design of the hybrid LFC-DSG system coupled with PCM-TES and back-up NG Boiler

A hybrid system model was developed using SAM hourly outputs of a modelled LFC solar field including thermal power output, average steam quality, outlet temperature, and mass flow. In addition to that the direct normal irradiation (DNI) and other weather conditions are also taken from the weather file. The model can use different collector specifications. In this particular case study, we used the SolAtom[®] modular LFC optical characterization and incidence angle modifiers (Kraemer, 2020).

Pittsburgh Pennsylvania, Tucson Arizona, and Lancaster California were selected as the test sites which have an average DNI of 4.10 kWh/m²/day, 7.36 kWh/m²/day, and 7.93 kWh/m²/day respectively (NSRDB, 2020). This then allows the North-East of the United States, and the South-West to be represented. As of 2020, the annual average industrial natural gas price estimated by the Energy Information Administration (EIA) was \$3.29 per thousand cubic feet (Mcf) or \$3.17 per MMBTU (EIA, 2021b, 2021c). The lowest annual average natural gas price observed in the United States since 1995 was \$2.71 per Mcf or \$2.61 per MMBTU (EIA, 2021d). Tab. 4 shows the 2020 average industrial natural gas prices and conversions used in the analysis.

	2020 Natural Gas Industrial Price (\$/Mcf)	2020 Natural Gas Price (\$/MMBTU)	2020 Natural Gas Price (\$/kWh _{th})
United States Average	3.29	3.17	0.011
Arizona	3.98	3.84	0.013
California	7.64	7.37	0.025
Pennsylvania	7.91	7.63	0.026

 Tab. 4: 2020 average Industrial Natural Gas Prices and conversions for U.S., Arizona, California, and Pennsylvania (EIA, 2021b, 2021c)

The heat load profile is set as 1 MW_{th} constant between 8am and 10pm, 0.2 MW_{th} constant between 12pm and 6am, ramping up to 1 MW_{th} between 6am and 8am in two steps $(0.47 - 0.75 \text{ MW}_{th})$ and fading down to 0.2 MW_{th} in two steps $(0.47 - 0.75 \text{ MW}_{th})$. This is similar to food processing/dairy sites in the United States (NAICS, 2021). For modeling simplicity, an 8-week test model has been defined with 2 weeks in winter, 2 weeks in spring, 2 weeks in summer and 2 weeks in fall which sums up to 1,345 hours of thermal power profile.

The model is designed to optimize the solar field size and the thermal storage capacity to meet a competitive LCOH. The summary of financial key inputs including the LFC system unit cost, PCM TES system unit cost, NG boiler total cost, carbon price, system lifetime and discount rate (10% for high-risk, 8% for moderate-risk, 7% and less for low-risk technologies) for the LCOH calculations are given in Tab. 5. The scenarios have been tested with and without the CO₂ cost. It is assumed that the same CO₂ price in California can be applied to Pennsylvania and Arizona, even though at present these two states do not currently have a carbon price.

An annual simulation model has been developed by using a multiplier of 6.5, though the 8-week model. Solar heat generation, thermal storage, curtailed solar energy, heat from natural gas and heat load profiles for representative two-week timeline (one week from winter and one week summer) are shown for California (Fig. 3), Arizona (Fig. 4) and Pennsylvania (Fig. 5).

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Tab. 5: Summary of key inputs for the LCOH calculations (*Minimum price available at auction per ton of CO₂ emissions in December 2020, in California's Cap-And-Trade Program (ICAP, 2021), **Conservative discount rate for a high-risk technology)

LFC System Cost (\$/m ²)	PCM System Cost (\$/kWh _{th})	CO ₂ Price* (\$/metric ton)	1 MW _{th} NG Boiler Cost (\$)	O&M (% of CAPEX)	System Lifetime (years)	Discount Rate** (%)
175	25	17.71	\$250,000	5%	25	10%



Fig. 3: Solar heat generation, thermal storage, curtailed solar energy, heat from natural gas and heat load profiles for representative two-week timeline (one week from winter starting from 168th hour and one week summer starting from 336th hour) in California



Fig. 4: Solar heat generation, thermal storage, curtailed solar energy, heat from natural gas and heat load profiles for representative two-week timeline (one week from winter starting from 168th hour and one week summer starting from 336th hour) in Arizona



Fig. 5: Solar heat generation, thermal storage, curtailed solar energy, heat from natural gas and heat load for representative twoweek timeline (one week from winter starting from 168th hour and one week summer starting from 336th hour) in Pennsylvania.

Results show that in the base scenario, \sim 3,600 m² of LFC solar field and 6 hours of PCM TES can provide up to 51% of the thermal load by solar energy, which leads to a significant reduction in natural gas consumption (Tab. 6). This results in a LCOH of \$0.049/kWh_{th} (\$14.26/MMBTU) for Pennsylvania, \$0.034/kWh_{th} (\$9.85/MMBTU) for Arizona, and \$0.041/kWh_{th} (\$11.98/MMBTU) for California (Fig. 6). The solar energy share of the total thermal load can be up to ~65% for a ~4,500 m² LFC solar field with 12 hours of PCM thermal storage. However, as seen in Fig. 6, at the present cost of the DSG-LFC and PCM TES system it is currently not yet fully competitive with the natural gas only system which has a LCOH of \$0.032/kWh_{th} (\$9.43 /MMBTU) in Arizona. This is mostly due to low natural gas price in 2020 and O&M cost. The annual average natural gas price observed in the United States was not always as low as 2020, the highest natural gas price was observed in 2008 as \$9.65 per Mcf or \$9.30 per MMBTU (EIA, 2021d). Thermal storage efficiency is the ratio of the energy provided to the energy needed to charge the storage system, which accounts for the energy loss during the storage period and the charging/discharging cycle. Storage efficiency can be as high as 84.70% for 6 hours of thermal storage in California.

State	Solar Field (m ²)	Storage Time (hrs)	Solar Share in Total Load (%)	Curtailed Solar Energy (%)	Storage Efficiency (%)	LCOH with CO ₂ adder \$/kWh _{th}	LCOH without CO2 adder \$/MMBTU	LCOH with CO2 adder \$/kWh _{th}	LCOH without CO2 adder \$/MMBTU
PA	2,890	6	26.01%	2.02%	63.41%	0.047	13.89	0.045	13.07
PA*	3,973	6	34.33%	4.57%	78.79%	0.049	14.26	0.046	13.54
PA	4,966	12	41.32%	0.32%	60.57%	0.051	14.95	0.052	15.17
CA	2,700	6	40.33%	1.78%	89.21%	0.041	11.92	0.038	11.26
CA*	3,600	6	50.98%	6.46%	84.70%	0.041	11.98	0.039	11.44
CA	4,501	12	63.32%	0.61%	72.76%	0.042	12.23	0.043	12.51
AZ	2,667	6	39.90%	1.68%	64.19%	0.032	9.43	0.030	8.68
AZ*	3,556	6	51.69%	6.85%	87.19%	0.034	9.85	0.032	9.41
AZ	4,455	12	64.42%	3.21%	79.32%	0.035	10.40	0.037	10.87

 Tab. 6: Summary of results for the hybrid system design in Pennsylvania, California, and Arizona (Conversion Factors: 1 cubic ft of natural gas = 1,030 Btu, 1 Btu = 0.000293071 kWh, *Base Case)



Fig. 6: Comparison of system LCOH for the natural gas boiler and the hybrid system of LFC-DSG with PCM TES and natural gas boiler back-up scenario in Pennsylvania, California, and Arizona (Base Case: solar multiple of 2, and 6 hours of thermal storage).

The capital cost of the hybrid system is estimated between \$1,022/kW and \$1,095/kW, which includes the additional \$250/kW NG boiler back-up system cost. This hybrid system can also provide up to 4,096 MWh_{th} natural gas offset which is equivalent to 757 metric tons of CO₂ emissions in Arizona, 4,009 MWh_{th} (741 tons of CO₂) in California, and 2,720 MWh_{th} (508 tons of CO₂) in Pennsylvania.

A sensitivity analysis is conducted to determine the break-even point for the hybrid system to have the equivalent LCOH as the standalone NG boiler system by changing the LFC cost and the natural gas price while keeping all other parameters constant. The LFC and NG price break-even points for the hybrid system modelled in Pennsylvania, California, and Arizona with CO_2 adder can be seen in Fig. 7, and Fig. 8 respectively.



Fig. 7: LFC cost sensitivity and break-even point for hybrid system in Pennsylvania, California, and Arizona with CO2 adder.

The break-even point for LCOH can be achieved if the LFC unit cost is equal to or lower than the represented values in Tab. 7. Similarly, the break-even point for LCOH can be achieved if the NG price is equal to or greater than the represented values in Tab. 7. The hybrid system can be feasible for an LFC system cheaper than the break-even price in Pennsylvania, Arizona, and California under the presented solar radiation, natural gas price, and the CO₂ credit.



Fig. 8: Natural gas price sensitivity break-even point for hybrid system in Pennsylvania, California, and Arizona with CO2 adder.

Tab. 7: Break-even LFC and NG prices for the hybrid system to have the equivalent LCOH as the standalone NG boiler system with
and without CO ₂ adder.

	Break-even LFC Cost	Break-even LFC Cost	Break-even NG Price	Break-even NG Price
	(With CO ₂ adder) \$/m ²	(Without CO ₂ adder) \$/m ²	(With CO2 adder) \$/MMBTU	(Without CO2 adder) \$/MMBTU
PA	229	167	6.4	7.6
CA	352	267	4.8	5.9
AZ	149	76	4.7	5.8

4. Discussion

From the heat pump model, it can be seen there is a balance between heat pump performance and capital costs. Although the heat pump that is hybridized with solar energy has the best COP of the group, the added costs of the solar collector increase the LCOH above poorer performing heat pumps. In the cases examined, the most economically competitive heat pump was the heat pump delivering 50°C heat with sewage as a heat source. For this work, it was assumed the sewage connection infrastructure was negligible which would not be the case, but these findings are in line with many heat pumps systems that are tied to sewage as a waste heat source. Overall, the cases show that there is some value to using upgraded waste heat temperatures to boost heat pump performance depending on the interconnecting infrastructure, which will require future research to better quantify.

Maximizing the share of solar energy in the LFC-DSG hybrid system design is not the most feasible solution for the industrial application due to high resulting LCOH. Optimizing the hybrid system with the best mix of natural gas and solar (i.e., 50-50) would give a competitive LCOH, thus the hybrid system could be feasible with respect to a standalone NG boiler system or a retrofit application. To make this system more competitive with natural gas only boiler systems, a carbon price of \$17.71/metric ton is added to the LCOH calculation, which is the minimum price at auction per ton of CO₂ emissions in California's Cap-And-Trade Program (ICAP, 2021). At present there is no carbon price system or mechanism for industry in the U.S. In addition to that, the natural gas price in the United States was not always as low as 2020. For instance, in 2008, it was three times more expensive than the natural gas price for industrial consumers in 2020 (EIA, 2021d). Further investigation will look at the increase in the natural gas price which would lead to an improvement in the break-even LCOH price of the hybrid system.

The LCOH results for Arizona show that at the present cost of the DSG-LFC and PCM TES system it is currently not yet fully competitive with the natural gas only system without the CO₂ cost adder. For Arizona, LFC systems should be installed up to $149/m^2$ to be competitive with the CO₂ cost adder. Without the adder, the unit cost should be as low as $76/m^2$. However, the hybrid system LCOH in California could be competitive and even better than standalone NG boiler systems due to high natural gas price. For California, LFC systems installed up to $267/m^2$ can still be competitive without the CO₂ cost adder. With the CO₂ cost adder, the unit cost can be as high as $352/m^2$. In addition to that, the hybrid system LCOH in Pennsylvania could be at break-even point compared to standalone NG boiler systems without the CO₂ cost adder. For Pennsylvania, LFC systems can be installed up to $167/m^2$ and still be competitive without the CO₂ adder. With the CO₂ cost adder, the unit cost can be up to $229/m^2$. Since the LCOH results are highly sensitive to energy prices, the volatility in natural gas prices can affect the feasibility of the RTES projects regardless of the renewable resource availability. As an example, in Europe, such hybrid systems may be a low-cost option for a variety of cases due to higher CO₂ prices and higher natural gas prices.

5. Future work

The work will continue to improve the LFC-DSG model by optimizing the system configuration and dispatch model. In addition to optimization, a series of sensitivity analyses are done including location, DNI, LFC solar field size, LFC installed cost, PCM thermal storage capacity, and natural gas boiler back-up size. The supporting infrastructure to increase adoption of heat pumps will be an important area for future research. Hybridization options for the HTHPs coupled with FPCs will be investigated. The capital cost considering economies of scale and learning in manufacturing, O&M cost and potential reductions, and system lifetime improvements will be investigated. Part of this future work will include a methodology to estimate the trade-off in capital cost investments vs. heat pump performance. As was seen in this study, upgrades to the waste heat stream can be cost-competitive (such as in the case of high-cost sewage vs. low-cost ambient to compensate for potential coupling costs), but up to certain costs can have diminishing returns depending on heat pump performance. The revenue creation through industrial heat generation, which will lead to an annual cash flow is likely to be investigated, and the payback period and internal rate of return for both greenfield hybrid system and retrofit applications would be calculated.

6. Acknowledgements

This work was authored by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. NREL does not endorse the companies specified in this paper, and any mention is strictly for research purposes only. Funding provided by the U.S. DOE of Energy Efficiency and Renewable Energy's Office of Strategic Programs and Advanced Manufacturing Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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IEA SHC Task 64/SolarPACES Task IV – SubTask C: Assessment of uncertainties in simulation tools

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Abstract

Solar Heat for industrial processes has been a topic addressed in two previous Tasks of the Solar Heating and Cooling Program. Despite the huge advances achieved regarding the new knowledge, the number of SHIP installations worldwide is still far from the expectations. Task 64/IV aims to address part of the persisting entry barriers for SHIP systems. In the frame of Subtask C, it has been proposed to conduct a comparison campaign between the available simulation tools for yield assessment, allowing to identify the sources of differences between the simulation approaches. Therefore, four case studies based on the configuration of actual plants have been defined. In this study 12 different simulation tools were evaluated. Significant differences were observed between the tools' output, reaching deviations up to 49% for one configuration. The deviations also depend on the time resolution and the control volume considered for the analysis. This assessment could represent an important contribution for the industry towards an unification of the simulation approaches, reducing the perceived risk by the stakeholders.

Keywords: Solar Process Heat, Simulation Tools, Yield Assessment

1. Introduction

Solar thermal technologies have been recognized by several authors as a reliable option for delivering process heat to industrial processes (Farjana et al., 2018; Sharma et al., 2017). In addition, solar heat for industrial processes (SHIP) has been thoroughly studied in two Tasks of the Solar Heating and Cooling Program (SHC), Task 33 and Task 49. Nevertheless, despite the efforts and progress achieved in building new knowledge and reducing the entry barriers that solar thermal technologies face in the industrial heat market, the number of solar heat plants for industrial processes is less than 1,000 installations worldwide (Weiss and Spörk-Dür, 2020). In that context, a joint task between the SHC and SolarPACES programs started in 2020, Task 64/IV. It comprises a collaborative effort bringing together the experience from professionals, project developers, and scientists, aiming to address part of the entry barriers that hinder the further development of the market. The research questions addressed in the context of the Task are the standardization of integration schemes at the process and supply levels, as well as the combination with other efficient heat supply technologies such as combined heat and power plants, heat pumps, or power-to-heat. Furthermore, the identification of standardized industrial load profiles and the uncertainties associated with the simulation tools commonly used for yield assessment are also part of the challenges addressed in Task 64/IV.

Task 64/IV is divided into five subtasks: A, B, C, D, and E. Subtask C aims to address the lack of a standard simulation tool for SHIP installations. Currently, there are several simulation tools available, and the results delivered by each tool may differ significantly from each other. Therefore, Task 64/IV subtask C integrates the knowledge established in the previous Tasks 33 and 49, but taking the information according to the industry's "common language". Hence, bringing together the know-how and experience of several experts working with heat integration and heat management tools. In that context, the main objective of the subtask is to develop a deep analysis of the available simulation and monitoring tools for assessing the potential benefits of integrating solar heat into industrial processes, with known uncertainty sources. To achieve the objective, certain activities are carried out as the

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identification of the currently available simulation tools, and the classification of them according to their capabilities, simulation approaches, and software restrictions. Furthermore, four case studies have been defined in order to conduct equivalent simulations in different simulation tools, and to compare the results, identifying the differences and the impact on the main performance indicators. Accordingly, based on the results obtained, a guideline for developing yield assessment of SHIP plants will be developed, similar to the work carried out in SolarPACES Task I: Guideline for Bankable STE Yield Assessment (Hirsch, 2017).

To include different solar thermal technologies and industrial processes, the four case studies are based on actual SHIP plants, which are currently in operation. For low temperature, first a large plant comprised of flat-plate collectors on fixed mount is considered. The second case study considers a solar field of flat plate collectors mounted on 1-axis tracking systems, which represents a new trend in the SHIP industry. Furthermore, to assess medium temperature applications two technologies are considered: linear Fresnel collectors operating in a Direct Steam Generation (DSG) scheme, and parabolic trough collectors using water-glycol as heat transfer fluid (HTF).

The interaction among the participants of Subtask C is done through bi-monthly meetings. There is a core team responsible for preparing the parameters of the case studies' plants, receiving the results, and performing the comparison routines. The present study reports the main findings of the assessment, describes the work carried out during the first half of the Task work plan, and summarizes the activities executed and the main results obtained. In this regard, from the comparison it is observed that important differences in the solar yield are detected. For instance, differences for annual results are up to -20.3% for case 1, 49% for case 2, 84.2% for case 4, and 41.9% for case 5. For smaller timescales, such differences increase significantly. Furthermore, the main sources of the differences are seemingly obvious, however the methodology employed in this study allows to quantify the differences. The main of difference observed are the modeling of the control scheme, the modeling of the heat exchangers, time shift between the TMY data and the solar position, the modeling of internal flows, the assumptions about thermal capacitances, and the modeling of the thermal storage (from fully mixed to stratified).

2. Methodology

Since one of the main objectives of the Tasks is to pursue the contribution, interaction, and discussion from several experts in the field, the authors of this study have been in continuous interaction with the Subtask C participants, who belong to different institutions around the globe. The authors have been working as a core team which leads and manages Subtask C activities, mainly providing the information to other participants, receiving the information, performing the analysis, and presenting the results.

For the specific activities that are covered in this study, i.e., the assessment of uncertainties in simulation tools, the highlighted section of the flowchart presented in **Fig.1** has been followed. First, a case study is selected. This means specifying a solar thermal installation currently in operation or being built. The main requisite is to have enough detailed information regarding the design (either public or private) to model the system in a simulation tool for yield assessment. For instance, the information should at least include the manufacturer and model of the collector employed (or performance curve), size, orientation and slope of the solar field, size, geometry and insulation characteristics of the thermal storage (if existing), details of heat exchangers, load profile (mass flow and temperature), and finally the control philosophy (including pump features).

In a second stage, all the technical information is compiled in a unique file (spreadsheet) that is distributed to the simulation specialist, who develops their simulation model in their preferred simulation tool. In addition to the technical features, the meteorological information (TMY format) is supplied along with a template spreadsheet to report the simulation results.

Once the results from the different analysts have been received, they are compared according to the metrics selected for this purpose, as detailed in Section 2.2. It is necessary to select one of the tools as a reference tool, which do not need to be the same for all the case studies. The comparisons are made considering different control volumes of the plant, according to the stages of energy flow, i.e., in the solar field, in thermal storage, and in the load to process. To assess the differences in the results reported, four time resolutions are considered for the comparison routine: hourly, daily, monthly, and annual values.

As a result of the comparison, the main sources of deviations between results from each simulation tool and the results of the reference tool are identified and quantified in a preliminary manner, according to the metrics employed. To improve qualitative analysis, bilateral meetings were held between the core team and each of the analysts during the first semester of 2021. The objective of these meetings is to understand the assumptions that the analysts have

considered, differentiating when they are due to lack of information about the system design, from the intrinsic limitations of modeling approach, and solution strategy of the software employed.

Feedback to the analysts is also given, based on the comparison of results. The aim is to enhance their models by improving the assumptions made due to lack of information, but not to alter their results to be closer to the reference tool. Hence, a second round of simulation is carried out, allowing to conduct an equivalent analysis and identification of sources of differences.

The final steps of the complete assessment, include the last three stages of the flow chart in Fig. 1, not presented in this study. Sources of differences are categorized according to the impact on the final energy yield. Since different software and different analysts might increase the bias and uncertainties in the analysis, a parametric analysis is performed varying the parameters associated with the sources of differences previously identified. This parametric analysis is carried out using one single reference tool and by the same analyst, with the aim of isolating (or reducing) the impact of the human factor. Finally, the final impact assessment and sources of differences are established.



Fig. 1: Flowchart of methodology utilized to identify the sources of differences in the results of energy yield performed by different analysts employing different simulation tools (software).

2.1. Definition of case studies

In order to cover a broader range of temperatures and applications, four case studies have been analyzed employing the methodology mentioned above. They are numbered 1, 2, 4, and 5 because the analysis of case study 3 is pending. Since this is an ongoing activity, the progress of the analysis is different for the 4 cases.

The information presented in this section summarize the main plant parameters and the operation scheme for each case study. However, there is more information available, and it was supplied to the analysts to build the simulation models, especially regarding hourly load profile, efficiency of solar field, geometry and insulation of the storage, effectiveness of the HXs, pumps mass flow and efficiency, control philosophy, among others.

Case study 1: flat plate collectors (FPC) to supply hot water to a copper mining process. The system supplies heat to a copper electrowinning plant located in the Atacama Desert, Chile (lat. 23.45° S, long. 68.81° W, annual GHI 2,631 kWh/m²). The plant is comprised by a 39,300 m² solar field of fixed flat plate collectors, with a thermal storage tank of 4,300 m³. The coupling scheme is considered through two heat exchangers, one between the solar field and the thermal storage tank, and the other between the storage and the load. A simplified layout for the plant is depicted in **Fig 2**. The HTF considered in the solar field is a water-glycol mixture (33% glycol), while the energy storage uses demineralized water. In addition, the working fluid of the process is water, where the set point temperature of the process is 70 °C and the return temperature is 40 °C. The annual heat demand is 94,171 MWh with a constant load profile (24/7) (Quiñones et al., 2020).

The solar field circuit is controlled by a differential temperature controller, which activates the circulation pump when the solar field outlet temperature is higher than the temperature at the bottom of the storage tank plus a dead band of 10 °C. In addition, a lower dead band of 2 °C is considered to turn the pump off. The temperature at the top of the tank is monitored for safety purposes to avoid boiling, so it deactivates the pump when it reaches 100 °C. On the thermal storage side and load circuit, since there is a fixed mass flow pump, the HX that supplies the load has a bypass to avoid heating the water to the process over 82.6 °C.



Fig. 2. System diagram of case study 1, flat plate collectors to supply hot water to a copper mining process.

Case study 2: 1-axis tracking flat plate collectors (FPC) to supply hot water to a paper mill process. The system supplies hot water as a preheating stage to a feed a gas boiler coupled to a paper mill factory located in Dordogne, France. The total gross collector area is $4,212 \text{ m}^2$, and the storage tank volume is 457 m^3 . The solar collectors are installed on a 1-axis tracking system that allows to maximize the heat production, and even reduce it, if necessary, by defocusing. The primary circuit (solar field) employs a water-glycol mixture as HTF. The make-up water to be heated is continuously provided by the demineralized unit of the paper mill. Both primary and secondary circuits employ variable-speed pumps controlled to maximize solar field output. The layout is depicted in Fig. 3. There is no fixed set-point temperature for the water delivered by the solar plant to the process. However, the maximum feedwater temperature to the boiler is 80 °C. The temperature setpoint to be reached at the collector outlet evolves throughout the year from 30 ° C (in winter) to 90 ° C (in summer), in order to maximize the production of solar heat.

The control strategy is the following. (a) when a threshold of irradiance on the surface of the collector is reached, the pump on the solar field circuit is turned on. At this point there is recirculation only on the solar field until the set temperature at the solar field outlet is reached. (b) When the set temperature is achieved, the flow goes through the heat exchanger and the pump of the secondary circuit is turned on. The pump operates in a closed circuit between the HX and the thermal storage. Both pumps are of variable speed and controlled to maximize the energy transfer at the HX, taking into account the set temperature at the solar field outlet. (c) When the process demands heat, water from the top of the thermal storage is employed. At the same time, cold water is pumped into the bottom of the tank to keep the volume constant.



Fig. 3. System diagram of case study 2, 1-axis tracking flat plate collectors to supply hot water to a paper mill process.

Case study 3: Pending. Case study on-hold while waiting for additional information to perform the uncertainty analysis.

Case study 4: linear Fresnel collector (LFR) for direct steam generation (DSG). The system analyzed corresponds to a system configured by the company Solatom, which consists of Fresnel FTL20 solar collectors. FLT20 modules are pre-assembled and packed at the factory, and then transported ready to be installed. Each module has a thermal power of 14.5 kW_{th} and is suitable for installation on rooftops. The system operates in the direct steam generation (DSG) scheme, and located in Seville (Spain), integrated in recirculation mode with a steam drum. The water-steam mixture generated by the solar field feeds the steam-drum, where the saturated liquid is fed back to the collector loop by the circulation loop. In case of sufficient pressure in the steam drum, the saturated steam is fed into

the conventional steam circuit (load). The total area of the reflective surface is 1900.8 m² and is structured in 6 loops with 12 modules each (the area of a single collector is 26.4 m²). The layout of the plant is depicted in Fig. 4. The annual heat demand is 4,858 MWh. The typical daily load profile is presented by de Santos López (2021). Saturated steam is provided to the process at 6 bar (158.5 °C), with the condensates returning at 70 °C. The steam demand is supplied by the solar system with the aid of a auxiliar natural gas boiler installed in parallel (not considered in the simulations) for low irradiation periods.

The control system is configured to maintain the operation conditions of the plant following these settings: (a) startup, boiler feed water recirculates in the field steam drum loop until pressure reaches the requirements; (b) normal operation, the steam from the steam drum is delivered to the steam line; (c) shutdown, decreases the mass flow rate as irradiation decreases, reaching a minimal value. The following control philosophy applies: if the nominal conditions could be met, go to recirculation; if the minimal flow rate is larger than the demand, go to recirculation; for operation on nighttime and/or low solar resource: "minimum flow rate in single collector loop".



Fig. 4. System diagram of case study 4, linear Fresnel collector (LFR) for direct steam generation.

Case study 5: parabolic trough collectors to supply hot water to a dairy plant. The system consists of a PTC field installed on the roof of a dairy factory, coupled to an existing system located in Saignelégier, Switzerland. A total of 17 PTC rows are installed, where one collector per row is implemented. The solar field operates with a waterglycol mixture, which is heated to a design temperature of 110°C. The HTF is sent to a heat exchanger with a nominal heat transfer rate of 350 kW. The thermal energy from the collectors is used to heat the pressurized water of the process up to a design temperature of 105°C. The hot water flows to the boiler and storage system of the plant, from where it is distributed to the processes involved in the dairy production. A simplified layout of the plant is depicted in Fig. 5.

The control strategy considered for the system is the following. When heat is required, and the direct solar radiation exceeds a predefined threshold (250 W/m²), the collectors are automatically turned towards the Sun and the pump starts to circulate. The flow rate in the solar circuit is controlled by a frequency converter to maintain the set temperature (between 110 and 120 °C). If this temperature exceeds the maximum allowed value, the sensor defocuses automatically. High-temperature shut-off happens only if high flow is detected. A shut down occurs when the direct solar irradiance is lower than 100 W/m².



Fig. 5. System diagram of case study 5, parabolic trough collectors to supply hot water to a dairy process.

2.2. Metrics for the assessment of differences/deviations

In order to configure a flexible tool for comparing the different simulation results of the cases under study, a unified open-source script for the treatment of hourly, daily, monthly, and annual time scales was programmed using Python; thus, different open-source packages were used. In this way, Matplotlib, Pandas, Numpy, and skill_metrics packages were used (Harris et al., 2020; Hunter, 2007; McKinney, 2010). These packages are useful both for data visualization and generation of figures for all time scales and for reading, processing, post-processing, and calculating statistical comparison parameters. In addition to that, Glob and Os packages were used to manipulate file paths. In this way, normalized root mean square (nRMSE), normalized mean bias error (nMBE), relative difference, the root mean square difference of the pattern (RMSD), Pearson correlation coefficient (R), and the standard deviation (σ) were calculated as established statistical comparison metrics. Nevertheless, at the hourly level, RMSD, R and σ were correlated within a Tylor diagram to visualize their deviation from the reference case. The pattern root mean square difference is presented in eq. 1.

$$RMSD = \sqrt{RMSE^2 + RMSE_{ref}^2 - 2 \cdot RMSE \cdot RMSE_{ref} \cdot R}$$
(eq. 1)

where RMSE is the root-mean-square of the tool to compare with the reference, $RMSE_{ref}$ is a root-mean-square of the reference, and R is the Pearson correlation between test and reference.

Furthermore, the Dynamic Time Warping (DTW) algorithm was employed for analyzing hourly results as a method to size and compare the time series difference between the results reported by the reference and the other tools, with respect to certain parameters. Currently, DTW is used in similarity tests, also for clustering and machine learning algorithms (Zhang et al., 2021). Thus, a typical code of the DTW algorithms is presented in the Tab. 1.

DTW algorithms
Input: Q = { $q_1, q_2,, q_m$ } and C = { $c_1, c_2,, c_n$ } // the two time-series
Output: The optimal warping path;
The distance of Q and C.
Initialize: $DTW(1,1) = d_{1,1}$
For i=1:n
For j=1:m
$D1 = d_{i,j} + DTW(i - 1, j)$
$D2 = d_{i,j} + DTW(i - 1, j - 1)$
$D3 = d_{i,j} + DTW(i, j - 1)$
DTW=min(D1,D2,D3);
The optimal $path_{i,j} = \min_{i} ((i - 1, j), (i - 1, j - 1), (i, j - 1))$
End
End

Tab. 1: Algorithm for computing the Dynamic Time Warping

Therefore, the purpose of using the DTW in this study is to quantify phase and amplitude errors, as well as to contrast the similarity between the temporal sequences with respect to the reference, and the sensitivity and relationship of DTW with other statistical established metrics (Gaspar et al., 2017). The main advantage of DTW over other established statistical metrics, such as RMSE and MBE, is related to the reliable alignment between the reference and test patterns. However, one of the main disadvantages of using DTW is related to a more robust computational effort to find the optimal alignment path in time (Brown and Rabiner, 2005).

Although the RMSE is more intuitive, it reports on the average size of the forecast errors regardless of their sign. Therefore, the biggest advantage of the RMSE is related to the measurement of uncertainty in the calculation of forecasts. However, two important disadvantages are observed; first, it is an absolute uncertainty metric that makes a comparison through highly variable time series, and that it is influenced by outliers. Therefore, it is not used to see the dynamic evolution of the series (Brown and Rabiner, 2005; Gaspar et al., 2017; Li et al., 2020).

2.3. Simulation tools employed

There was no restricting criterion for selecting the simulation tools. Any participant of the Subtask C that was trained in a simulation tool and willing to contribute was welcome. Hence, it was possible to include in the study licensed software, open-source software, and in-house developed software. The participants/analysts also delivered a brief simulation log together with the results where the main assumptions and limitations of the software for a specific component were indicated, e.g., if the software cannot model the thermal storage losses, a penalizing factor is added by the analyst to the energy yield. Tab. 2 summarizes the tools/software employed for each case study.

Case study 1	CEA model, Greenius, SHIP2FAIR tool, SHIPcal, System Advisor Model (SAM) TRNSYS - TESS library, TRNSYS - basic library.
Case study 2	NewHeat tool, Polysun, SHIP2FAIR tool, TRNSYS (3 simulations models employing different libraries)
Case study 3	Status: pending
Case study 4	Greenius, SAM, Scilab, SHIP2FAIR tool, SHIPcal, TRNSYS (4 simulation models employing different libraries)
Case study 5	Greenius, Polysun, TRNSYS

Гab.	2.	List of	tools/software	employed	for th	ne different	case studies.
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3. Results and Discussion

In order to compare the simulation results from the different simulation tools and cases, a reference tool is selected for each case. The "deviations" of the results between the different tools and the reference are calculated using the metrics described in Section 2.2. The reference tool is named Tool 0 for all case studies. When available, Tool 0 corresponds to the tool employed by the project developer during the design stage of the SHIP plant. The tools have been purposely randomly numbered for the benchmark analysis to avoid the unintended message of ranking the tools.

Case study 1. The annual and monthly energy delivered to the load for case study 1 is presented in Fig. 6. It can be observed that in the annual analysis tools 1 and 2 overestimate the energy yield, and tools 3, 4, 5, and 6 underestimate it. There are no large differences in the output (up to 6.45%), with the exception of tool 5 which underestimate the energy to the load by 20.3% when compared to the reference. The monthly results indicate a similar behavior in the shape of curves, but certain values highly disagree. For instance, tool 5 delivers 35% less energy to the load compared to the reference in June.



Fig. 6. Annual and monthly figures of energy yield to the load obtained by the different tools for case 1.

The Fig. 7 (left) presents a daily comparison of the different DTW profiles between the reference tool and the other tools used in the analysis. The comparison is shown in terms of the absorbed solar radiation (q_{in}) , heat to the TES (q_{hx1}) , and the heat to the load (q_{hx2}) . The first plot shows a low value for the DTW for all tools, except for tool 6 (yellow lines), suggesting that a different approach for the weather input is used for this simulation. Its effect is also

observed in the other control volumes. For the rest of the tools, it is noticeable that the indicator increases its value as it goes through the control volumes in the direction of the energy flow (from irradiation to load). Therefore, it is observed that the different assumptions and simulation approaches may contribute to the overall error as the simulation model increases in number of components. On the right plot of Fig. 7, certain days are selected to present the hourly evolution. It can also be observed that tool 6 has a mismatch in the TMY data compared to the rest. In addition, for the heat supplied to the load (q_{hx2}) it is observed the effect of the thermal storage modeling. The periods where the curve saturates to a constant value are explained by assuming an approach with a single-node tank. Thus, it charges and discharges at continuous energy rates between the set and the minimum temperatures. On the other hand, the periods where the curve increases and decreases with a steady slope means that the tank is stratified. Hence, the tank can deliver lower energy rates due to a lower outlet temperature.



Fig. 7. Dynamic Time Warping (DTW) on daily timescale (left) and hourly profiles for selected days (right) for Case 1.

Case study 2. Similarly to case study 1, the annual and monthly energy yield for case study 2 are presented in Fig. 8. In this case the results reported by tools 1 and 4 are extremely similar to the reference tool, both in annual and monthly time resolution, with an annual difference under 1%. On the other hand, results reported by tools 2, 3 and 5 underestimate annual and monthly values of energy delivered to the load. These differences are -8.3% for Tool 3, -27% for Tool 5 and -49% for Tool 2. Monthly results agree with the annual values. However, there is a trend during certain months of the year, where the difference between some tools and the reference tool is higher, i.e., tools 2, 3, and 5. The difference increases during summer months with higher solar resource availability. Conversely, during winter months, such as December or January, there are smaller absolute differences with the reference tool.



Fig. 8. Annual and monthly figures of energy yield to the load obtained by the different tools for case 2.

Case study 4. The annual and monthly energy yield to the load for case study 4 are presented in Fig. 9. In this case, the results reported by tools 1, 3, 5, 6, and 7 are similar to the reference tool, with an annual deviation under 10%. In addition, the results reported by tools 4 and 8 underestimate annual energy delivered to the load, with an overall

difference of -19.5% and -17.7%, respectively. For monthly values, tool 8 underestimates in summer (April to September). Moreover, although Tool 4 is close to the reference in July and August, it consistently underestimates the energy yield from November to June, and overestimates in September and October. Furthermore, Tool 2 presents the largest difference with the reference tool. It presents significant higher values, for both annual and monthly results, overestimating in 84.2% the annual value of the reference.



Fig. 9. Annual and monthly figures of energy yield to the load obtained by the different tools for case 4.

Case study 5. For this case study only 3 sets of results have been collected (depicted in Tab. 2). Therefore, the comparison analysis has not been concluded. However, Fig. 9 present the annual and monthly energy yield. As preliminary observations, for annual values Tool 1 underestimates the energy supplied to the load (-11%), whilst Tool 2 greatly overestimates it (41.9%). When the monthly figures are observed, it is noticeable that Tool 1 underestimate the energy yield in winter months but overestimate it in summer. Tool 2 has an odd behavior with high peaks in March and June, which leads to overestimate the overall energy yield.



Fig. 10. Annual and monthly figures of energy yield to the load obtained by the different tools for case 5.

To summarize the results from the comparison analysis, Tab. 3 presents the differences observed in the total energy yield to the load for the 4 case studies, when compared to each reference tool. The normalized RMSE is presented for the monthly values, whilst the percentual difference is presented for the annual values.

In addition, Tab. 4 presents the values for the DTW from the hourly comparison normalized by the annual load. The table is separated by case study and tool. For each case study different control volumes are analyzed, i.e. the supplied energy is calculated at different stages of the energy flow to the load. For example, for case study 1 three control volumes are considered: (a) solar field, where the incident radiation on the collector's surface is calculated; (b) heat exchanger between solar field and storage tank, where the energy transferred to the tank is calculated; and (c) heat exchanger between the storage tank and the load, where the total energy yield to the load is calculated. The DTW represents a cumulative distance from the reference, hence lower DTW are desirables. It can be observed that DTW increases when the control volume is closer to the load (maximum values). It means that the deviations of the simulation results at different components impacts the next component on the direction of the energy flow to the load. Frequently, the monthly and annual values hide certain differences when integrating the values over the period,

as positive and negative deviations are compensated.

Case	Value	Time scale	Metric	tool 1	tool 2	tool 3	tool 4	tool 5	tool 6	tool 7	tool 8
1	Energy	Monthly	nRMSE	0.05	0.04	0.07	0.07	0.21	0.08	-	-
to load	to load	Annual	% diff.	4.03	2.32	-6.5	-6.5	-20.3	-6	-	-
2 Energy to load	Energy	Monthly	nRMSE	0.07	0.69	0.18	0.06	0.49	-	-	-
	to load	Annual	% diff.	-0.05	-49	-8.3	-0.12	-26.8	-	-	-
4	Energy	Monthly	nRMSE	0.06	0.88	0.02	0.33	0.07	0.09	0.08	0.31
to	to load	Annual	% diff.	5.30	84.2	-1.6	-19.5	6.1	8.3	8	-17.7
5	Energy	Monthly	nRMSE	0.31	0.74	-	-	-	-	-	-
	to load	Annual	% diff.	-11	41.9	-	-	-	-	-	-

Tab. 3. Summary of the differences observed from the simulations in the four case studies.

Tab. 4. Summary of the comparison results in terms of the DTW.

Case	Parameter	Normalized DTW %	Tool 1	Tool 2	Tool 3	Tool 4	Tool 5	Tool 6	Tool 7	Tool 8
1	Incident	min	1.34	1.07	1.45	1.45	1.12	8.73	-	-
	radiation	max	4.41	4.42	3.61	3.61	2.79	71.83	-	-
	Energy to	min	1.44	3.69	3.63	3.63	7.73	3.38	-	-
	TES	max	9.25	9.24	8.84	8.84	42.79	32.34	-	-
	Energy to	min	2.51	13.12	11.54	11.54	7.44	1.83	-	-
	load	max	56.03	32.99	31.83	31.83	104.91	35.78	-	-
	Incident	min	0.30	0.53	0.29	0.24	0.29	-	-	-
	radiation	max	7.61	33.82	11.21	10.59	26.95	-	-	-
2	Energy to TES	min	0.00	0.07	0	0	4.21 e-05	-	-	-
2		max	9.91	37.46	13.46	17.21	20.39	-	-	-
	Energy to load	min	0.04	0.07	0.79	0.38	0.57	-	-	-
		max	21.0	65.47	38.64	20.24	34.76	-	-	-
	Incident radiation	min	8.02e-8	5.33e-17	4.56e-4	2.46e-16	0.29	NA	0	0
4		max	0.014	5.39	0.004	2.13	16.39	NA	1.45e-14	1.45e-14
-	Energy to load	min	0	0.42	0	0.23	3.10e-05	NA	0	0
		max	5.56	34.98	19.72	18.67	18.78	NA	15.06	18.99
5	Incident radiation	min	2.21	3.15	-	-	-	-	-	-
		max	14.27	85.93	-	-	-	-	-	-
5	Energy to	min	0.19	0.19	-	-	-	-	-	-
	load	max	47.46	138.65	-	-	-	-	-	-

Notes: - For case 1, tool 6 presents a high DTW value for the incident radiation due to initialization of the operation variation. - For case 4, tool 6 did not report hourly results.

From the analysis of the DTW results and the direct comparison of hourly curves, the main sources of difference are identified. For instance, time delays or shifting between the reference and the tools are due to shift in the sun position, consideration or not of the components' heat capacitance, and modeling of the control philosophy. In addition, certain absolute differences of energy flow are due to modeling of the thermal storage (stratified, hot and cold tanks, or fully mixed), modeling of the heat exchangers, and considering the thermal losses of piping.

4. Conclusions

The present study describes the initial results obtained by the comparison campaign of simulation tools employed for yield assessment of SHIP plants. The motivation of the study was associated to the large number of simulation

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tools available in the market, lacking a standardized one. Moreover, it was noticed that most of the project developers employ their in-house developed tools. The main advantage observed regarding the different tools is the broad range of system configurations that can be modeled, and the high flexibility that most of the tools present. However, certain tools have been developed to model specific systems and do not perform appropriately for technologies different from the original, e.g., a software developed for tracking-concentrating systems employed for non-concentrating collectors. Therefore, to ensure that the results obtained from the yield assessments can be directly compared it is necessary to develop a guideline for performance comparisons of SHIP simulations, like the work carried out for CSP systems.

The activities performed within the Subtask C have been highly time-consuming. Nevertheless, the participation of more than 30 experts and analysts from different international institutions enriches the feedback obtained for the analysis and increases the opportunity of understanding several different simulation approaches. Although the results of the comparisons seem to be evident and expected, several deviations observed were not directly linked to assumptions that might be trivial. For instance, the meteorological data is commonly an input for the simulations (usually in TMY format); however, the software's internal radiation processor can incorrectly use a different time stamp than the one from the meteorological file.

Regarding the comparison of the results obtained from the simulation tools, several anomalous behaviors are noticed. First, for annual values certain cases present large deviations from the reference tools (up to -20.3% for case study 1, 49% for case study 2, 84.2% for case study 4, and 41.9% for case study 5). Since the annual energy yield hides several short-term effects, e.g., seasonal variations, the differences observed are too high to assume that the SHIP plants performance is correctly estimated. Hence, the risk for the financial assessment increases, and consequently, the competitiveness of solar thermal technologies against non-renewable is highly reduced.

The assessment described in the present article could initially aid unifying criteria for modeling assumptions and defining simulation approaches. With further analysis it also aid in reducing the "risk" perceived by the financial industry and facilitating the interaction with the potential consumers. This is an ongoing study. Since relevant deviations in the results were observed at this stage, that only considers simulations, actual operation data will be employed in a second stage of the project. The operation data will be employed as the reference to assess the differences in the plant performance estimated by the simulation tools. Finally, the key findings of these comparisons will serve as input to create guidelines for implementing computational tools to assess and monitor the performance of SHIP systems, which are part of the deliverables of Subtask C.

5. Acknowledgments

The authors gratefully acknowledge all the participants of Task 64/IV subtask C that have contributed with the simulations, in particular to J. Dersch and J. Labairu (DLR), R. Albert (CEA), A. Gonnelle (NewHeat), M. Nájera (CIMAV), G. de Santos (KTH), A. Cazorla (UPV), D. Theiler (SPF), E. Burin (UFPR), P. Kurup (NREL), M. Frasquet (SOLATOM).

The authors also acknowledge the financial support from ANID/FONDAP 15110019 "Solar Energy Research Center" - SERC-Chile and the project ANID/FONDECYT/1191705. A. Pino acknowledges financial support from ANID PFCHA/DOCTORADO BECAS CHILE/2017. I. Arias acknowledges the funding from ANID PFCHA/Doctorado Nacional 2021-21210053. Finally, this study was partially funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, via a scholarship to Leonardo Freire Lacerda Lemos.

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Towards the Optimal Design and Control of Solar–biomass Heating Networks for Greenhouse Applications: Methodology and Preliminary Results

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Abstract

Greenhouses are productive facilities very suitable for the consideration of distributed schemes for their energy management, including solar radiation as one of their main primary sources. This paper focuses on the optimal sizing and control of solar-biomass heating networks to be used in greenhouse environments. The methodology employed is a bi-level optimization strategy in which the lower layer, which is based on the energy hubs concept, is responsible for the optimal dispatch of the heating network, trying to reduce the operating costs while meeting demand. The upper layer includes a surrogate optimization algorithm in charge of performing the optimal sizing of the heating network to minimize the investment and long-term operating costs. Besides, this optimization problem includes some constraints such as the minimum desired solar fraction. A case study based on real facilities located in Almería (Southeast of Spain) is employed as an application example in order to show the promising outcomes achieved with the proposed methodology. The preliminary results are analyzed, regarding the economic viability, by means of the discount payback time and Levelized cost of energy.

Keywords: District heating, Energy hubs, Multi-level optimization, Sizing, Process Control.

1. Introduction

It has become clear in recent years the growing concern about building a sustainable and efficient energy sector. In this new panorama, renewable energies and carbon-neutral technologies play a major role in reducing emissions and in the transition to the energy sector of the future. Among the different options, solar-biomass cogeneration plants have emerged as an effective solution to sustainably supply heat to industries (Tilahun et al. 2021, Gil et al. 2021); especially in semi-arid areas where the availability of solar irradiance is high (Mouaky and Rachek, 2020). In such locations, these facilities and greenhouses synergize with each other, and an opportunity presents itself to use agricultural residues as biomass (Vallios, 2009). In addition to the above, these hybrid schemes are also very suitable even for isolated greenhouses thanks to the integration of storage systems (Sethi et al. 2013). Nevertheless, to exploit the benefits of these hybrid plants, it is important to i) optimally manage the energy generation and dispatch according to the resources available at each moment, through adequate control systems, and ii) reduce the investment costs through an appropriate optimal design.

Until now, there are few studies in the literature dealing with the optimal design or control of these kinds of hybrid facilities (Suresh et al., 2019; Tilahun et al. 2021). Moreover, the methodologies presented in them are mainly focused on the design, without paying attention to the optimal dispatch, yet the independent optimization of the plant size and energy management in hybrid plants can lead to performance degradation (Shu et al. 2020). The main reason is that hybrid systems normally present different operating modes that must be managed according to the available resources and energy demand to improve the operating costs. The introduction of these operating details in the design phase could be essential to reach correct plant designs as stated by Evins (2015). This can be achieved by developing optimal design procedures based on detailed process simulations.

However, the optimal design based on these detailed simulations entails a high computational burden which stands out as one of the main barriers for the development of these kinds of techniques. In this regard, the use of the Energy Hubs (EH) concept can be a good option to formulate the dispatch problem and simulate the optimal operation of the system. EH is not a novel concept but it was proposed some years ago to refer to any system in which input energy or material flows can be converted into certain output resources and stored (Geidl et al. 2006). Based on the internal structure, it is possible to establish a mathematical model to represent these processes together with the physical constraints of the system. What is more, each system's component can be characterized by a static or time-varying conversion factor, hence the computational burden of the problem is considerably reduced. As a result, EH is a wide applicability concept for systems including energy or material resources in which certain variables can be controlled, and others not, as the hybrid facility at hand in this study.

Even though the use of the EH approach can diminish the computational burden of the simulations, for design purposes, the system's simulations are used to adjust the sizing parameters (i.e., solar field area, biomass power system). This could give rise to a problem when using optimization frameworks to perform the design, as these techniques require many simulations before converging and meeting given performance requirements. Consequently, the use of conventional optimization methods is often impractical and even prohibitive because of time requirements. This issue can be alleviated by using the so-called surrogate optimization approach, which diminishes the number of time-consuming cost function evaluations by using models that reliably represent it in a much simpler and analytically tractable way (Queipo et al., 2005).

By following the aforementioned ideas, this paper presents a bi-level optimization technique for the optimal sizing and control of solar-biomass heating networks in the environment of greenhouses. This technique takes into account the interdependencies and relations among the design and the operating phases to obtain suitable solutions. To do that, the upper layer employs a surrogate optimization algorithm in charge of selecting the optimal design of the heating network. This algorithm is connected to a lower optimization layer that uses the energy hubs approach to determine how energy should be dispatched. Thus, the objective functions of the two layers consider both the operating and investment costs of a case study based on an "Almería-type" greenhouse, which has been chosen to exemplify this methodology. It must be remarked that the formulation of the EH dispatch problem is the main progress and contribution in relation to our previous work in Gil et al. (2021), in which the dispatch problem was solved through a rule-based controller.

The rest of the paper is organized as follows: Section 2 presents the case study, the formulation of the management and design problems, and describes the proposed bi-level optimization technique. Besides, it also depicts the main performance metrics used to evaluate the adequacy of the solution provided by the algorithm. Section 3 shows the results obtained with the application of the proposed technique to the case study, and, finally, Section 4 summarizes the main findings.

2. Material and methods

2.1. Case study

In this study, a hybrid thermal network including a biomass boiler and a solar thermal field is employed to meet the demand of a greenhouse. This demand is associated to the thermal energy required to maintain the desired temperature range for the crops. Fig. 1 presents the schematic diagram of the case study.



Fig. 1: Schematic diagram of the case study.

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As can be observed in Fig. 1, the case study is composed of an "Almeria-type" greenhouse, a solar thermal field of flat-plate collectors, and a biomass boiler. The solar field and biomass boiler act as producer agents regarding the heating network, whereas the greenhouse is a heat consumer. The possibility of storing thermal energy is also contemplated. Besides, the electricity network is included to satisfy the needs of the solar field pumping systems. It should be remarked that all these facilities are based on real plants located in the Almeria province (Southeast of Spain) and they were fully described and modelled by Rodriguez et al. (2015), Sánchez-Molina et al. (2014), and Gil et al. (2020). In this way, the case study constitutes a real representative environment that allows us to encompass actual experiences and production concerns, which is of vital importance to validate the adequacy of the proposed method and the applicability of the obtained results.

2.2. Bi-level optimization framework

The main objective of this work is to develop a bi-level optimization technique that exploit the synergies between the design and operational phases. For this purpose, the developed algorithm has been divided into two layers related to each other as shown in Fig. 2 (see Plant design and energy hub blocks in the figure).



Fig. 2: Schematic diagram of the proposed bi-level framework.

In the proposed framework, first, the thermal energy demand of the greenhouse is calculated by using a validated model of an "Almeria-type" greenhouse. The reader is referred to Rodriguez's et al. work (2015) in which the model was fully described. Note that it has not been included in this work for the sake of brevity. Besides, a meteorological dataset of the selected location is required to simulate this model and the heating network's. Then, the communication between layers within the bi-level optimization framework can be depicted as follows:

- i. The sizing parameters (i.e., storage capacity, solar field size, and biomass boiler power) provided by the design optimization algorithm (plant design block in Fig. 2) are sent to the lower layer (energy hub block in Fig. 2).
- ii. In the lower layer, the sizing parameters are used to configure the EH model of the system and the optimal dispatch (trying to minimize the operating costs) is performed through a Mixed Integer Linear Programming (MILP) optimization problem. Once the dispatch is finished, the results in terms of operating costs are sent to the sizing layer in order to calculate the new value of the objective function.

The procedure described above is repeated continuously until the optimization algorithm of the design layer converges to the global solution. The following subsections describe each of the blocks of the bi-level optimization technique as well as the optimization problem included in each one.

2.3. Energy hub model and control problem formulation

The model for scheduling the energy dispatch is based on the general approach presented previously by Ramos-Teodoro et al. (2018), which has been adapted for the greenhouse environment (Fig. 1). By using this approach, each of the system's components can be modelled through one or several (in case more than one type of energy is required) input ports, referred to any kind of energy stream; a conversion factor, for modelling the conversion of energy or resources; and an output port, which represents the demand of any kind of energy. Thus, as illustrated in Fig. 3 and depicted in Tab. 1, the energy hub of the case study counts with electricity (I_1) coming from the public utility grid, solar radiation, (I_2), and biomass (I_3) as inputs; and with electricity (O_1) and heat (O_2) as outputs. Note that O_1 is only an actual consumption if the field of solar collectors is activated ($\delta_{D,1}$) to produce heat.



Fig. 3: EH characterization of the case study.

Tab.	1:	EH	inputs	and	outputs	description.
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Index	Inputs (<i>Ii</i> in Fig. 3)	Outputs (Oi in Fig. 3)
1	Electricity from the power grid [kW]	Electricity for the solar collectors [kW]
2	Incident radiant power on the solar facility [kW]	Thermal power for the greenhouse [kW]
3	Wood pellets for the biomass boiler [kg/h]	-

The conversion and storage processes are expressed as in equations (1) and (2), respectively. These are matrixial expressions where O, Q_c , Q_d , and S are vectors whose size depend on the number of outputs (see Fig. 3 and Tab. 1), P is a vector that depends on the system's structure (readers are referred to Ramos-Teodoro's et al. study for clarification), $\delta_O(k)$ is the identity matrix with the element (1,1) substituted by $\delta_{D,1}$, and the remaining matrixes express losses in conversion (C), charging (C_c), discharging (C_d) and storing (C_s) operations.

$$\begin{split} & \boldsymbol{\delta_0}(k)\boldsymbol{0}(k) = \boldsymbol{C}(k)\boldsymbol{P}(k) - \boldsymbol{Q_c}(k) + \boldsymbol{Q_d}(k) & (\text{eq. 1}) \\ & \boldsymbol{S}(k+1) = \boldsymbol{C_s}(k)\boldsymbol{S}(k) + \boldsymbol{C_c}(k)\boldsymbol{Q_c}(k) - \boldsymbol{C_d}(k)\boldsymbol{Q_d}(k) & (\text{eq. 2}) \end{split}$$

It is important to remark that the conversion factor of the solar field can be easily calculated by using the thermal collector efficiency equation (Allouhi et al. 2017), whereas the one of the biomass boiler can be computed according to boiler's overall efficiency and the Lower Heating Value (LHV) of the biomass. Both efficiency parameters are given by:

$$\eta_{sf}(k) = \eta_o - a_1 \cdot \left(\frac{T_m(k) - T_A(k)}{G(k)}\right) - a_1 \cdot \left(\frac{(T_m(k) - T_A(k))^2}{G(k)}\right)$$
(eq. 3)
$$\eta_{bb} = \eta_b \cdot LHV$$
(eq. 4)

Where η_{sf} is the conversion factor of the solar collector field, which relates the radiant power received by this system and the corresponding thermal power delivered. η_o is the solar collector optical efficiency, a_1 is a thermal losses parameter (W·m⁻²·K⁻¹), a_2 is also a thermal losses parameter (W·m⁻²·K⁻²), T_m and T_A are the mean and ambient temperature (°C), respectively, and *G* is the incident irradiance (W·m⁻²). On the other hand, η_{bb} is he biomass boiler efficiency, which relates the biomass flow and the heat flux generated, and η_b is he boiler efficiency.

Moreover, and following with the EH formulation, equation (5) relates input vector
$$I$$
 with vector P :
 $I(k) = C_i P(k)$ (eq. 5)

In addition to the equations that limit the flows through either conversion or storage devices, the storage and selling capacity, and the availability of input resources, which for the sake of conciseness are not included in this work; equation (4) is required to avoid charging and discharging, at the same time, the heat storage device.

$$\delta_{c,2}(k) + \delta_{d,2}(k) \le 1$$
 (eq. 6)

Finally, the optimization problem is defined by means of equation (7) that includes de economic cost of acquiring resources (c(k)).

min $\sum_{k=1}^{24} \boldsymbol{c}(k) \boldsymbol{I}(k)$	(eq. 7)
s.t. the above restrictions	

2.3. Design optimization problem

The objective of the design optimization problem consists of computing the sizing parameters that provide the lower costs, including both operating and investment costs, while meeting demand. For this purpose, the optimization problem can be posed as follows:

$\min J = C_{inv}(x) + \sum_{k=1}^{N} \frac{C_{op}(x) + C_m(x)}{(1+r)^k}$	(eq. 8)
s.t.	
$SF(\mathbf{x}) \ge SF_{min}$	(eq. 9)
$x_{low} \le x \le x_{up}$	(eq. 10)

In this formulation, C_{inv} is referred to the investment costs, C_{op} to the operating costs, and C_m to the maintenance costs. The two last costs are expanded in a time horizon, referred by symbol N in the formulation, considering a discount rate denoted by r. The vector of decision variables (x) is composed of the solar field size, the biomass system's maximum power, and the capacity of the thermal storage system. In addition, the optimization problem is subject to some constraints related to the Solar Fraction (SF), where SF_{min} represents the minimum desired value, and the limits of the decision variables, where x_{low} and x_{up} are referred to the lower and upper limits, respectively. It should be remarked that, to solve this problem, the *surrogateopt* solver of MATLAB software (MATLAB, 2020) was used since the evaluation of the objective function is time-consuming.

2.4 Performance metrics

To assess the viability of the solution provided by the bi-level optimization technique, two different economic metrics has been selected. The first one is the well-known index Levelized Cost of Heat (LCOH). This metric

provides information about the cost of energy production, and can be calculated as the ratio between the total life cycle cost and the total lifetime energy produced by the power facility as follows:

$$LCOH = \frac{C_{inv} + \sum_{j=1}^{N} \frac{c_{op} + c_m}{(1+r)^j}}{\sum_{j=1}^{N} \frac{Q}{(1+r)^j}}$$
(eq. 11)

Where Q is the heat (kWh) delivered by the system (i.e., solar field or biomass power generation system) under study, and the rest of the parameters has been defined previously.

Besides, the inherent risk of the project has been also evaluated by using the discount payback time. This metric determines when profit generations starts or, in other words, when the cash flow turns positive. The discount payback time can be calculated by using the Cash Flow (CF) per year, which is given by:

$$CF(i) = -C_{inv}(i) + \sum_{j=1}^{i} \frac{-C_{op} - C_m + C_{savings}}{(1+r)^j} \quad \forall i\{1, \dots, N\}$$
(eq. 12)

Where *i* is the year under study, and $C_{savings}$ is related to the savings obtained with the hybrid system in comparison with the cost of a conventional power system. It should be commented that in the first year, CF is negative; but the year in which the cumulative CF becomes positive, the discount payback period is reached.

3. Results

3.1. Simulation set-up.

The bi-level optimization methodology was applied to a cluster of greenhouses with a total cultivation area of 20 ha of tomato, which serves to illustrate the developed methodology in the design of a solar-biomass heating system. In this cluster, the setpoint temperature to compute the heating demand of the greenhouse was stablished at 14 and 21 °C for the night and day periods, respectively; typical setpoint temperatures used in agricultural holdings in Almería as described in Gil et al. (2021). As a preliminary approach, a time horizon of a week was considered in the lower layer and meteorological data of a typical week in Almería (in the winter period, which is the one with the highest demand for heating) was used to generate the thermal demand of the greenhouse. Concretely, Meteornorm v7 Typical Meteorological Year (TMY) for a representative coastal location at the province of Almería was used during the days 11-18 of January.

In the upper layer (design optimization problem), the results obtained in the lower one (i.e., operating costs) were extrapolated to a time horizon of 20 years (which is N=20) considering a discount rate r of 0.03. These parameters were chosen according to Tian et al. (2018). In addition, a minimum solar fraction of 20 % was imposed to ensure a minimum solar energy contribution.

To calculate the investment costs, a price of $200 \text{ } \text{e} \text{ m}^{-2}$ and $62 \text{ } \text{e} \text{kWh}^{-1}$ were considered for the solar thermal field and storage systems (Evins, 2015), respectively. The investment cost of the biomass system was computed with the relation presented by Vallios et al. (2009). Then, the term C_{op} is the objective function value of the lower layer optimization problem, whereas C_m was calculated as a percentage of the investment costs using the equations presented by Pakere and Blumberga (2020).

In the lower layer, the EH model was configured with $\eta_0 = 0.775$, $a_1 = 3.72 \text{ W} \cdot \text{m}^{-2}\text{K}^{-1}$, $a_2 = 0.016 \text{ W} \cdot \text{m}^{-2}\text{K}^{-2}$, and $T_m = 60 \text{ °C}$. Besides, η_b was fixed at 0.8, and the LHV of the biomass at 4.86 kWh·kg⁻¹, which corresponds to the heating value of pellets at 8% moist. Most of these parameters come from real experiences or certification from the actual facilities as reported in Gil et al. (2021).

3.2. Optimal sizing

As commented, the *surrogateopt* solver of MATLAB software (MATLAB, 2020) was used to work out the design optimization problem due to the high computational burden required. Besides, within de optimization procedure, a week of hourly data was used to simulate the system and to perform the optimal dispatch in the lower layer of the bi-level optimization framework. The latter was solved using *intlingprog* solver also from MATLAB. The main benefit of considering data on such a small-time scale is that it allowed us to perform a much more precise design of the hybrid heating network taking into account the time-varying demand of the greenhouse. Thus, the optimal sizing values provided by the algorithm are presented in Tab. 2.

Plant sizing		Investment cost [€]	Operating cost per week [€]
Solar field size [m ²] 7,600		1,520,000	805
Biomass boiler maximum power [kW]	5,305	563,120	21,530
Thermal storage capacity [kWh]	10,000	620,000	-

Tab. 2: Value of the optimal sizing parameters.

The optimal size of the field of solar collectors was found to be 7,600 m², the maximum power of the biomass system was 5,305 kW, and the thermal storage capacity was 10,000 kWh. This system configuration led to total investment cost of 2,703,120 \in , of which around 58 % corresponded to the costs of the solar collector field, 20 % to the ones of the biomass system, and 22 % to the ones of the thermal storage system.

3.3. Optimal management

This section presents the performance of the hybrid system in daily operation, which was optimally managed through the lower layer of the bi-level optimization framework. The optimal scheduling performed by the EH management technique is presented in Fig. 4. In this figure, the first graph presents the irradiance (yellow bars) and the charge level of the storage tank (green dashed line), whereas the second one reflects the greenhouse demand (red area) and the production of the solar and biomass systems (which are represented by light and dark green bars, respectively).





One should take into account that the main particularity that happens in this case study is that the demand of the greenhouse and the solar field production are decoupled in time as observed in Fig. 4. By and large, the demand of the greenhouse is mostly produced at night when the ambient temperature is low, so that an additional supply of thermal energy is needed to maintain the desired temperature for crops. This disparity supports the application of the developed bi-level optimization technique using an hourly basis simulation.

Regarding the dispatch performed by the EH optimization method, on the first day, all the demand of the greenhouse was supplied by the biomass system since there was no thermal energy stored in the storage tank. In addition, as the level of irradiance was very low (below 250 $W \cdot m^{-2}$ as the sky was overcast) the solar field was not used along the day. Thus, during the second night, all the demand was covered by the biomass system again.

In contrast, on the second day, the panorama was different since the solar field could be turned on. In this way, the energy delivered by this system was stored in the storage system being then used during the night to partially cover the greenhouse demand. This allowed us to reduce the biomass system's contribution leading to a much more efficient and sustainable operation in terms of emissions to the environment. In the rest of the days, the behavior was similar, that is, the higher the production of the solar field, the more energy could be stored in the tank and, therefore, the lower the production of the biomass system. This was especially noticeable in the last day, where, in addition, the greenhouse demand was lower than in the previous days.

3.4. Economic analysis of the solution provided by the algorithm

The solution provided by the bi-level optimization framework must not only be technically analyzed, but also its economic viability must be assessed. For this aim, the LCOH and the discount payback period were studied.

Firstly, the LCOH was calculated for each energy source using the optimal results provided by the algorithm, resulting in 0.052 and 0.041 \notin ·kWh⁻¹ for the solar and biomass systems, respectively. This confirms that the design carried out provided reasonable values in terms of cost of energy if one compares the obtained results with reference values in literature. For instance, in the work by Tilahun et al. (2021) the LCOH of a biomass system was studied, showing that prices of up to $0.10 \notin$ ·kWh⁻¹ could be reached depending on the price of biomass. For the case of the solar field, prices of around $0.35 \notin$ ·kWh⁻¹ were reported in the work by Bhusal et al. (2020).

The obtained LCOH values can be also compared with the ones of other energy sources, mainly fossil fuels, employed in greenhouse environments such as natural gas or diesel. The reference LCOH of the gas natural is $0.05 \ ckWh^{-1}$, but this figure can be higher if there are no nearby natural gas distribution networks. Besides, the price of the diesel can reach up to $0.45 \ ckWh^{-1}$ in off-grid locations of Spain as discussed in the work by Soltero et al. (2018). These reference values confirm the viability of the obtained solution and suggest that the proposed hybrid system is especially attractive to be implemented in off-grid locations without access to the gas natural distribution network.

Finally, the discount payback time was studied. As this metric is highly dependent on the fuel price used for comparison purposes, since it influences the term $c_{savings}$ in equation (12), different fuel prices were considered ranging from 0.05 to $0.15 \ ckWh^{-1}$. This range was chosen to encompass from the reference value of natural gas to the value that this source can attain in off-grid locations. The results obtained are reflected in Fig. 5.



Fig. 5: Discount payback time as a function of different fuel prices.

As observed, the system was not profitable when comparing with fuel prices lower than $0.07 \notin kWh^{-1}$. From this value on, the discount payback time was reasonable. For example, for a value of $0.08 \notin kWh^{-1}$, the discount

4. Conclusions

This paper addressed the optimal sizing and operation of solar-biomass heating networks for the environment of a greenhouse. For this aim, a bi-level optimization technique based on the EH concept is proposed and exemplified by using a representative case study in the province of Almería (Spain). From the obtained results, the following conclusions can be drawn:

- The proposed bi-level optimization algorithm resulted in an attractive tool to perform the design of solarbiomass hybrid systems for processes with time-varying demand, as the case study conducted.
- The use of the EH concept has resulted in a powerful technique to address the optimal operation of the system. Indeed, it can be used to reflect the optimal operation in the real system as long as appropriate low-level controllers are implemented.
- Regarding the economic results, LCOHs of around 0.05 and 0.04 €·kWh⁻¹ for the solar and biomass systems, respectively, were obtained. This confirmed the profitability of the obtained solution in comparison with reference values in literature.
- Also, the discount payback period analysis performed indicated the suitability of these facilities especially for isolated regions with fuel prices over 0.08 €·kWh⁻¹.

Future work will be focused on optimization considering a whole year in the lower layer and exploring the inclusion of other thermal demands that may be present in these environments to obtain greater profitability.

Acknowledgments

This work has been carried out as part of the project entitled "MICRORREDES PARA EL AUTOABASTECIMIENTO SOLAR DE ENTORNOS PRODUCTIVOS AISLADOS (MICROPROD-SOLAR)" funded by the International Joint Programming initiative of the State Research Agency of the Spanish Government, grant PCI2019-103378 and by the Iberoamerican Program for Science and Technology for the Development (CYTED).

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Appendix: Acronyms and Symbols

Table 1: Acronyms

Acronym	Description
CF	Cash Flow
EH	Energy Hubs
LCOH	Levelized Cost of Heat
LHV	Lower Heating Value
MILP	Mixed Integer Linear Programming
SF	Solar Fraction
TMY	Typical Meteorological Year

Table 2: Symbols

Quantity	Symbol	Unit
Thermal losses	a ₁	$W \cdot m^{-2} \cdot K^{-1}$
parameter	1	
Thermal losses	a_2	$W \cdot m^{-2} \cdot K^{-2}$
parameter	-	
Investment costs	C_{inv}	€
Maintenance costs	C_m	€
Operating costs	Co	€
Savings obtained with	$C_{savings}$	€
the hybrid system	0	
Incident irradiance	G	$W \cdot m^2$
Time horizon	N	years
Heat	Q	kWh
Discount rate	r	-
Minimum desired solar	SF_{min}	-
fraction		
Ambient temperature	T_A	°C
Mean temperature	T_m	°C
Lower limit of decision variables	x_{low}	-
Upper limit of decision variables	x_{up}	-
Vector of decision	x	-
Poiler afficiency	22	
Diamaga hailar	η _b	-
efficiency	Прр	-
Conversion factor of	η_{sf}	-
the solar collector		
field		
Solar collector optical	η_o	-
efficiency	-	

Meaning	Symbol	Unit
Vector containing the	с	Multiple
price of each input		units
of the energy hub		
Coupling matrix	С	Multiple
1 2		units
Diagonal matrix of	C.	-
charge efficiencies	-0	
Diagonal matrix of	C.	-
discharge	- <i>u</i>	
efficiencies		
Input coupling matrix	C.	-
Diagonal matrix of	C_{1}	-
resource	03	
degradation		
Vector of input flows	I	Multiple
vector of input nows	-	units
Flement of <i>I</i>	I	Multiple
	1	units
Vector of output flows	0	Multiple
vector of output nows	0	unite
Flament of O	0	Multiple
	0	unite
Vector of flows	D	Multiple
between inputs and	r	with
outputs or "path		units
vector"		
Vector of charge flows	0	Multiple
vector of charge nows	\mathbf{Q}_{c}	unite
Element of O	0	Multiple
Element of Q_c	Q_c	with
Vector of discharge	0	Multiple
flow	Q_d	with
Flomont of O	0	Multiple
Element of Q_d	Q_d	with
Vector of stored	c	Multiple
	3	with
Flomont of S	c	Multiple
Element of 3	3	with
Pinory variable for	2	units
abarging best	0 _{c,2}	-
Dinamy variable for	6	
discharging host	0 _{d,2}	-
Dinamy variable for the	6	
field's electricity	<i>o</i> _{<i>D</i>,1}	-
acomposition		
Dinory diagonal matrix	2	
Element of $\boldsymbol{0}$ Vector of flows between inputs and outputs or "path vector" Vector of charge flows Element of \boldsymbol{Q}_c Vector of discharge flows Element of \boldsymbol{Q}_d Vector of stored resources Element of \boldsymbol{S} Binary variable for charging heat Binary variable for discharging heat Binary variable for the field's electricity consumption Binary diagonal matrix	Ο P Q _c Q _d Q _d S S δ _{c,2} δ _{d,2} δ _{D,1}	units Multiple units Multiple units Multiple units Multiple units Multiple units Multiple units Multiple units - -

MILP Algorithm for outlet temperature optimization of a hybrid concentrated solar thermal system for SHIP considering a 1D solar field and a dual phase thermocline storage

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Abstract

Solar Heat for Industrial Processes (SHIP) is in an increasing trend in research for industrial decarbonization. Process heat demand and solar energy can both present large intermittencies. Storage gives a degree of freedom on which mathematical optimization can be performed. Lowering the working temperature of the solar field decreases the heat losses and therefore maximizes the production; it also reduces heat losses from the storage while increasing its use in the operational phase. In this paper, the investigated system is a solar field consisting of low-cost Parabolic Trough Collectors in series with Linear Fresnel Receivers, in series with a dual-phase thermocline storage. A MILP (Mixed Integer Linear Programming) algorithm is used in order to obtain a control trajectory of the system; then, this control trajectory is injected in a non-linear and more accurate plant model to evaluate its performances. Comparison is performed with another control approach, consisting in producing at the process temperature whenever possible. The MILP control shows an absolute increase of the solar fraction of 2.5%. The way the thermocline is handled is not standard (as compared to what is done for electricity production) but shows a great interest for heat applications.

Keywords: MILP, SIPH, SHIP, concentrated solar thermal, concentrated solar heat, operating temperature optimization, flexible heat integration, process heat, storage, system modelling, control strategy, dual-phase thermocline

1. Introduction

Heat, this low exergy energy often discredited in public debates, where electricity has the foreground, represents 50% of the final energy consumed in 2019 (IEA, 2020), with electricity and mobility representing 20% and 30% respectively. Heat production, in 2019, emitted 13.3 Gt-CO₂-eq., which corresponds to 40% of total emissions.

Among this 50% of heat, half is used by industrial processes and 47% for heating and domestic hot water, the 3% remaining being for various uses. It is consequently urgent to decarbonize heat for industry if humanity wants to keep the actual level of production without suffering from the consequences. Many renewable solutions allow a decarbonization of heat; the most used today are biomass (~79% of renewable heat in industry), electricity from renewable sources (~10%) and heat from heat networks (~3%). Solar thermal is unfortunately not much used today. Indeed, solar thermal has often been criticized for its price and the space required for its implementation.

In Europe, gas prices are currently under market pressure, having reached €108/MWh in October 2021; the resilience and independence of our industrial systems are thus naturally questioned.

It seems more and more obvious that, for temperate climates and installations in non-desert areas (and, as a result, where space is limited), the solar energy cannot be a unique source of energy along the year. Consequently, it must be hybridized. Hybridization with wind energy, by mechanical wind turbine and Joule effect (Okazaki et al., 2015), as well as biomass, would enable an effective form of resilience to be achieved. Production could be adapted to the availability of energy, if too many external constraints appear in future supplies. Investment in these energies and research is therefore increasingly seen as a modern emergency. We assume in this work that the industry must run at the planned schedule: the heat demand is considered immutable, although some works (Fitsum et al., 2018) showed the interest of managing demand.

In this article, we will discuss the hybridization of a solar field with a boiler. As the boiler operates at high temperature (and thus with higher exergy), it is interesting to reduce the temperature at the exit of the solar field, thus increasing the solar performance and reducing the fuel requirements. This concept of Flexible Heat Integration was proposed by (Rashid et al., 2019). A previous article (Kamerling et al., 2021) has been published
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on a similar optimization, with two-tank storage. MILP (Mixed-Integer Linear Programming) algorithms have been widely used in the optimization of solar thermo-electric power plants, such as (Pousinho et al., 2014; Yang et al., 2018).

In this paper, a MILP algorithm is used to obtain a control trajectory, which is then applied to a more complex model, taking into account nonlinearities. The purpose of this paper is to share model developments, considering a 1D solar field and a dual phase thermocline storage.

The first part (section 2) presents the investigated system and the general co-simulation approach used in this paper. The second part describes the implemented solar field and the thermocline 1D models; the third part describes the MILP algorithm and the associated control, as well as an alternative control approach enabling a comparison of the results. In the fourth part, the results of a case study are given.

2. Proposed system and modeling approach

2.1. System under consideration

2.1.1. Diagram and description of the studied solar concentration system

The system chosen in this study is a solar field consisting of low-cost parabolic trough collectors (PTC) in series with higher efficiency Linear Fresnel Receivers (LFR), the solar field being in series with a thermocline storage, although it is possible to bypass the storage and to go directly to the boiler.



Fig 1. Diagram of the solar thermal system studied and the variables of interest

In Figure 1, we can see on the left, the solar field (described in section 3.1); in the middle, the thermocline storage (section 3.2); on the right, the boiler. The variables in black correspond to the input data of the model, those in red correspond to the control trajectory obtained from control algorithms (section 4) and those in blue are deduced from the control trajectory (section 3.3).

The Heat Transfer Fluid (HTF) enters the system with a mass flow rate \dot{m}_{demand} , at a temperature T_{return} . It has to be sent to the process at the temperature T_{demand} , both being constants along the year. If the storage is in discharge mode (outlet temperature $T_{out,d,st}$), some or all of the fluid may enter the thermocline storage; part of this flow (\dot{m}_{aux}) comes from the control trajectory, whereas the other part is deduced from the operating mode ($\dot{m}_{st \rightarrow boiler}$). From the point of view of control algorithms, \dot{m}_{aux} allows the solar field to be bypassed. Passing it through storage resets the thermocline. If the storage is in charge mode (outlet temperature $T_{out,c,st}$), part of the

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flow comes from the storage $\dot{m}_{SF \rightarrow st}$, which means that the inlet temperature of the solar field $T_{in,SF}$ has to be recalculated, in case the outlet temperature of the storage is significantly higher than the process return temperature T_{return} .

2.1.2. Main assumptions

Different assumptions and approximations have been made in this model: the main objective is to compare the different control approaches:

- the quality of the forecast: this is not taken into account, i.e. the meteorological data are assumed to be known in advance. This means, *de facto*, that we are on a probabilistic trajectory corresponding to the median of the probabilities. One way to overcome this assumption would be to use Robust MILP algorithms, such as (He et al., 2016), which allows taking into account the quality of the forecast and making decisions upon the robustness of the solution,
- constant efficiency of the boiler (taken at 100%): this assumption is very accurate in a wide range of operation, the value of 100% is taken as it does not influence the results presented here,
- solar modules' inertia is taken as the contained fluid's inertia,
- no headers were considered in this study, although they add some inertia to the system,
- the chosen HTF is Therminol 66, and its properties are all taken at 1 bar; dependence on temperature is taken into account through interpolation of fluid properties,
- time discretization is hourly.
- 2.2. Modelling approach

Figure 2 shows the modelling approach followed by the algorithm. To calculate the outcomes over the year, a loop is performed every 24h.

Before entering the loop, the algorithm reads the input data, and chooses the design if specified. The outlet temperatures of the solar field are discretized.

At the beginning of the loop, the solar field model calculates the producible mass flow for the different discretized temperatures, considering inertia.

Then, an optimization algorithm chooses the optimal control trajectory upon 48h. The control trajectory is then fed into the non-linear model, which then calculates the heat production and boiler requirements, as well as the storage state and other variables of interest (in blue in Fig.1.), upon 24h. Both storage and solar field final states are then passed as input to the loop. The optimization is run over 48h in order to optimize the storage dispatch for the next day as well (else, the storage is just emptied by the optimization algorithm).

This kind of control strategy is commonly referred to as Rolling Horizon (Moretti et al., 2021).



Metrics and data analysis

Fig. 2. Algorithm structure

3. 1D Models

3.1. Solar Field Model

In the present study, the solar field consists of low-cost Parabolic Trough Collectors (from Absolicon) followed by Linear Fresnel Receivers (from Industrial Solar), permitting to reach higher temperatures. This association allows some installations to gain on the cost of the heat produced (FriendSHIP, 2021).

The solar field is modelled in one dimension, with calculations on each module, and this in a quasi-static approach: a stationary calculation is made, then the thermal inertia is translated into a loss or a gain in terms of mass flow, in the manner of the SAM model (Wagner and Gilman, 2011).

Fluid properties are obtained by interpolation. They are assumed to only depend on the temperature.

3.1.1. Optical efficiency and thermal losses

The calculation of the optical efficiency is done in two different ways depending on the collector technology:

- The PTC *via* a longitudinal $IAM_{L,PTC}$ (Incidence Angle Modifier), multiplied by the cosine of the longitudinal angle : $\eta_{opt}(\theta_L) = \eta_{0,PTC} * IAM_{L,PTC}(\theta_L) * \cos(\theta_L)$
- The LFR *via* a longitudinal $IAM_{L,LFR}$ and a transversal $IAM_{T,LFR}$, in which is already included the cosine effect: $\eta_{opt}(\theta_L, \theta_T) = \eta_{0,LFR} * IAM_{L,LFR}(\theta_L) * IAM_{T,LFR}(\theta_T)$

With θ_L and θ_T the longitudinal and transversal angles respectively, and η_0 the optical efficiency at normal incidence, with subscripts corresponding to the concerned module. The end losses are not taken into account, although they are probably significant in the case of small or medium size installations, located in latitudes corresponding to continental Europe. The module incident energy is then written as: $\dot{q}_{in} = G_b * \eta_{opt}(\theta_L, \theta_T) * A_{collector}$, with G_b the beam irradiation in $W.m^{-2}$ and $A_{collector}$ the aperture area in m² of a module.

The heat losses are written in a general way: $\dot{q}_{losses}(\Delta T) = A_{collector} * \sum_{i=1}^{4} a_i \Delta T^i$, with: $\Delta T = \frac{T_{in}+T_{out}}{2} - T_{amb}$ being the average fluid temperature difference with the ambient, T_{in} being the inlet temperature of a module, T_{out} the outlet temperature and T_{amb} the ambient temperature. The a_i , $i \in [1; 4]$ are the heat loss coefficients (from correlations) and are in $W.m^{-2}.K^{-i}$.

3.1.2. Stationary calculation of the outlet temperature of a loop

Knowing the mass flow rate and the inlet temperature, and after calculating the optical efficiency, the outlet temperature of a module is calculated by solving the following equation:

$$\dot{m} * C_p * (T_{out} - T_{in}) = \dot{q}_{in} - \dot{q}_{losses}$$
 (1),

with \dot{m} the mass flow rate in $kg.s^{-1}$, C_p the fluid specific heat capacity in $J.kg^{-1}.K^{-1}$, T_{in} and T_{out} being respectively the inlet and outlet HTF's temperatures in the SF. This equation is a quartic equation in T_{out} . The fluid properties are taken at the inlet temperature.

The calculation of all temperatures in the loop is then performed from one module to another, considering for the module n the outlet temperature of the module n-1.

3.1.3. Quasi-static calculation of the mass flow rate

The output temperature being fixed, the calculation is done in two steps: first, the stationary mass flow rate is calculated, by dichotomy on the outlet temperature, via Eq.(1). Then, the energy needed to heat the content of the modules (thermal inertia) to reach their temperature is accounted for, and converted to a mass flow rate before being subtracted from the stationary flow. This is calculated as follows:

$$E_{inertia} = \sum_{i} V_i * \rho(\overline{T}_{i,h}) * \left(h(\overline{T}_{i,h}) - h(\overline{T}_{i,h-1})\right) (2) ,$$

with V_i the HTF volume contained in module i in m^3 , ρ the density in $kg.m^{-3}$, h the enthalpy of the HTF in $J.kg^{-1}$, \overline{T} the average temperature of the module (calculated by averaging inlet and outlet temperatures), the subscripts h and h-1 referring to the time h and h-1.

The conversion to mass flow rate is then done in the following way: $\dot{m}_{inertia} = \frac{E_{inertia}}{h(T_{SF})^{*3600}}$ (3)

The mass flow rate of the solar field is then written $\dot{m}_{SF} = \dot{m}_{stationary} - \dot{m}_{inertia}$ (4).

3.1.4. Validation

The validation of the solar field 1D model was done using the "Linear Fresnel with Molten Salt" model of the open-source software SAM. Using SAM inlet and outlet temperatures, the hourly mass flow rates were calculated with the above model and compared to SAM's hourly mass flows.

The average relative error of the daily energy production is 2.6% - highest peaks in relative error occur when the daily production is very low. The average relative error on the hourly flow rate is 6.9%. The main reason for the deviations is that in SAM the molten salt/water heat exchanger before entering the turbine has a large thermal inertia, while there is no heat exchanger in the present model. Figure 3 shows the daily heat output of the two models, as well as the relative error between both.



Fig.3 : Daily heat production of SAM model (yellow) and the model presented here (blue), with relative error in % on the right (red) 3.1.5. Definition of defocusing

Defocusing has been defined in two ways: firstly, defocusing in series, i.e. in a loop, in order not to exceed the maximum temperature of a collector or not to exceed the output temperature. The defocusing fraction is then defined by: $defocus_{Serie} = \frac{A_{defocalised}}{A_{loop}}$ (5)

Then the parallel defocusing, which consists in defocusing a certain number of loops, in order not to exceed a certain mass flow (full storage, etc.). It is calculated as a ratio between the chosen mass flow and the one that can be produced at the desired outlet temperature: $defocus_{//} = 1 - \frac{m_{SF}}{m_{possible}}$ (6).

Note that the real defocus is not continuous; however, we are working on a large solar field, which makes the approximation acceptable.

Table 1. Parameters of the PTC

3.1.6. Input parameter values

Parameter (unit)	Value	Description
η_0	0.697	Optical efficiency at normal incidence
$A_{collector}(m^2)$	5.51	Collector surface area
$a_1(W.m^{-2}.K^{-1}))$	0.73	Heat losses coefficient
$\dot{m}_{nom}(kg.s^{-1})$	0.126	Nominal mass flow rate

Table 2. Parameters of the LFR

Parameter (unit)	Value	Description
η_0	0.686	Optical efficiency at normal incidence
$A_{collector}(m^2)$	30.45	Collector surface area
$a_1(W.m^{-2}.K^{-1})$	0.033	Heat losses coefficient
$a_4(W.m^{-2}.K^{-4})$	1.48e-9	Heat losses coefficient
$\dot{m}_{nom}(kg.s^{-1})$	0.6	Nominal mass flow rate



Fig.4. IAM of the collectors – transversal IAM of the LFR (blue), longitudinal IAM of the LFR (yellow), longitudinal IAM multiplied by cosine of the longitudinal angle of the PTC (green)

3.2. Dual-phase thermocline

It was chosen to work with a dual-phase thermocline because this storage is cheap, as it consists of only one tank and a large proportion of the often expensive HTF is replaced by a low-cost solid.

3.2.1. Implemented model description

The thermocline model implemented is the one of a dual-phase thermocline, from (Hoffmann et al., 2016), with the correlations from (Esence et al., 2019). It is a model with three partial differential equations: one for the fluid temperature, one for the solid temperature and one for the wall temperature. The resolution of this system involves a one-dimensional discretization over the tank's height. The discretization chosen for the convection term depends on the fluid flow direction:

- Downwind differencing scheme for tank's discharge (rising fluid): $u \frac{\partial T}{\partial x} = u * \frac{T_j T_{j-1}}{\Delta x}$
- Upwind differencing scheme for tank's charge (dropping fluid): $-u \frac{\partial T}{\partial x} = -u * \frac{T_{j+1} T_j}{\Delta x}$

The use of the QUICK scheme would be preferable in general cases, but the above formulation is sufficient to have a convergence of the model with liquid fluids. The time discretization is implicit, because the explicit discretization showed very quickly a divergence in the results.

The model is solved using the open-source library *DAE-CPP* (Ikorotkin, 2019), itself based on the free IBM library *Math Kernel Library*.

3.2.2. Validation

This model has been validated with an in-house code, itself validated on experimental data from the STONE installation at CEA Grenoble (Esence et al., 2017).

The validation was done in the following way: a sequence of charges and discharges at different temperature levels were simulated in both models, then a calculation of the temperature difference was done using interpolations, in order to measure the deviation due to the numbers of elements:

$$err = \frac{1}{\Delta t} * \frac{1}{L} * \int_0^L \int_0^{\Delta t} \frac{|T_{ref}(z,t) - T(z,t)|}{T_{ref}(z,t)} dt dz$$

For a number of elements equal to 100 (the reference number of the in-house model), we found a difference of 0.9%. For 50 elements, this difference rises to 2.6%, but we have chosen to work with 50 elements as the computation time of the storage depends strongly on this parameter.

Nonetheless, varying the temperature at the inlet (as done further) can create modelling inaccuracies, as the stratification may be disturbed; furthermore, this model does not take into account buoyancy. This would need a deeper modelling for better validation.

3.2.3. Calculation of a threshold HTF mass

Hot fluid should not be sent back in the solar field. There should therefore be a temperature threshold, traduced as an HTF injected mass threshold which should not be exceeded by the control trajectories. This mass is not obvious as the thermocline is filled with solid particles. Taking the temperature threshold as: $T_{threshold} = T_{discharge} + \frac{1}{3}(T_{charge} - T_{discharge})$, a serie of simulations (charge mode) with a constant mass flow rate showed

that the HTF mass threshold that could be injected to reach the temperature threshold was about $M_{threshold} = \rho_{HTF} * V_{tank}$. This result does depend on the mass flow rate but appeared to be a good enough value.



Fig.5. Storage outlet temperature (continuous line) during a load, with three different mass flow rates; mass injected into the storage (dashes), with the colours corresponding to the flow rates; $M_{threshold} = \rho_{HTF} * V_{tank}$ with the pink crosses; and $T_{threshold}$ with the green crosses

Figure 5 shows the outlet temperature of the storage under charging, at a constant mass flow rate, for a storage volume equal to 465 m^3 . The second vertical axis indicates the mass injected into the storage. It can be seen that the storage outlet temperature increases by about 1/3 of the temperature difference when a mass of $M_{thresgold} = \rho_{HTF}(T_{hot}) * V_{tank}$ has been injected in the storage. This remains dependent on the mass flow rate and not perfectly precise.

3.2.4. Definition of the charge percentage

The energy contained in the storage is defined as:

$$E_{storage} = \int_{0}^{L} (\epsilon * \rho_{HTF}(T_{HTF}(z)) * h_{HTF}(T_{HTF}(z)) + (1 - \epsilon) * \rho_{solid} * h_{solid}(T_{solid}(z)) * A_{tv} dz$$
(7)

With ϵ the rock bed global void fraction, ρ , h, T the density, enthalpy and temperature respectively, the subscripts HTF and solid referring to the different materials involved, and A_{ty} the cross-sectional area of the tank.

By defining E_{max} the stored energy when $\forall z, T_{HTF}(z) = T_{solid}(z) = T_{process}$ and by defining E_{min} the stored energy when $\forall z, T_{HTF}(z) = T_{solid}(z) = T_{return}$, we can define the charge percentage $\tau = \frac{E_{storage} - E_{min}}{E_{max} - E_{min}}$ (8).

3.2.6. Input parameters

Parameter (unit)	Value	Description
€ (-)	0.27	Rock bed global void fraction/ HTF Volumetric fraction
$d_p(m)$	0.015	Equivalent diameter of solid particles
$U_{eq}(W/m^2.K)$	0.1	Heat losses coefficient
<i>e_{wall}</i> (m)	0.012	Thickness of the metal wall
$C_{p,solid} \& C_{p,wall}(J/kg.K)$	900 & 500	Specific heat capacity of the solid filler and the wall's metal
$\rho_{solid} \& \rho_{wall} (\text{kg}/m^3)$	2500 & 7200	Density of the solid and the wall
$k_{solid} \& k_{wall}$ (W/m.K)	5 & 20	Thermal conductivity of the solid and the wall
N _{discr}	50	Number of elements of the thermocline's discretization

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3.3. System model

In this section, the solar thermal system response to the control trajectory is explained; this latter is therefore assumed to be known, i.e., $(\dot{m}_{SF}, T_{SF}, \dot{m}_{aux})$.

Determination of the storage operating mode

The mass flow rate of the demand must be assured, which gives:

 $\dot{m}_{demand} = \dot{m}_{SF \to boiler} + \dot{m}_{st \to boiler} + \dot{m}_{aux}$ (10)

The flow coming from the solar field can go either to the storage or to the boiler, which gives:

$$\dot{m}_{SF} = \dot{m}_{SF \to boiler} + \dot{m}_{SF \to st}$$
(11)

We can then write the variation of the inlet and outlet mass flow of the storage:

$$\Delta \dot{m} = \dot{m}_{SF \to st} - \dot{m}_{st \to boiler} \ (12)$$

The reinjection of Eq.(10) and Eq(11) in Eq(12) gives:

 $\Delta \dot{m} = (\dot{m}_{SF} - \dot{m}_{SF \rightarrow boiler}) - (\dot{m}_{demand} - \dot{m}_{aux} - \dot{m}_{SF \rightarrow boiler}) = \dot{m}_{SF} + \dot{m}_{aux} - \dot{m}_{demand}$ (13)

The sign of $\Delta \dot{m}$ then gives the operating mode of the storage.

Case 1: Storage load: $\Delta \dot{m} > 0$

It can be deduced that $\dot{m}_{st \to boiler} = 0$, and thus from Eq.(12) that $\dot{m}_{SF \to st} = \Delta \dot{m}$. Moreover, one must then necessarily have $\dot{m}_{aux} = 0$, because no control model attempts to load the storage while not producing at least the demand mass flow rate.

We deduce from Eq.(12) and Eq.(13) that $\dot{m}_{SF \rightarrow boiler} = \dot{m}_{SF} - \dot{m}_{SF \rightarrow st} = \dot{m}_{demand}$.

The outlet temperature of the storage is then calculated according to $\dot{m}_{SF \to st}$, which gives us an outlet temperature of the storage, noted $T_{out,c,st}$. The inlet temperature of the solar field can then be calculated:

$$T_{in,SF} = \frac{\dot{m}_{SF \to st} * T_{out,c,st} + \dot{m}_{demand} * T_{return}}{\dot{m}_{SF \to st} + \dot{m}_{demand}}$$
(14)

This last one can be quite high if the thermocline zone starts to exit the tank. This is why a mass threshold should be set for those control models. Nonetheless, verification is performed, as well as reactualization of mass flow rates:

- If $T_{in,SF} + 10^{\circ}C$ is higher than the outlet temperature of the solar field, an attempt is made to run the solar array at the demand temperature, and the flow rates are updated accordingly. Note that this shows a flaw in the control trajectory.
- If not, we recalculate the production of the solar field. If the calculated flow is lower than the flow of the trajectory m_{SF} , the latter is lowered, and the mass flows are updated. If the calculated mass flow rate is greater than the trajectory mass flow rate m_{SF} , this is considered as parallel defocusing.

Case 2: Storage discharge: $\Delta \dot{m} < 0$

We then deduce that $\dot{m}_{SF \to st} = 0$, and thus that $\dot{m}_{st \to boiler} = -\Delta \dot{m}$. It was chosen, given the thermocline type of storage, that \dot{m}_{aux} goes through the thermocline storage (see section 2.1), in order to reset the thermocline and recover a maximum of energy.

The mass flow rate through the storage to the boiler $(\dot{m}_{st \rightarrow boiler})$ becomes: $-\Delta \dot{m} + \dot{m}_{aux}$. The storage outlet temperature is then determined by the thermocline model; it is noted $T_{out.d.st}$.

Case 3: Storage inactivity: $\Delta \dot{m} = 0$

In this case, the control system does not discharge the storage, and we have: $\dot{m}_{SF} = \dot{m}_{SF \rightarrow boiler}$ and $\dot{m}_{demand} = \dot{m}_{aux} + \dot{m}_{SF}$. Due to the implemented logic of thermocline's reset, i.e., that \dot{m}_{aux} passes through the storage, we take: $\dot{m}_{st \rightarrow boiler} = \dot{m}_{aux}$.

The storage outlet temperature is then determined by the thermocline model.

From this data, the boiler requirement is deduced:

$$\dot{q}_{boiler} = \dot{m}_{SF \to boiler} * \left(h(T_{process}) - h(T_{SF}) \right) + \dot{m}_{st \to boiler} * \left(h(T_{process}) - h(T_{out,d,st}) \right)$$
(15)

4. Control models

Two control approaches are considered: one from MILP optimization and one from a simple control approach so that the benefit of the MILP algorithm can be evaluated.

4.1. MILP algorithm

For the sake of brevity, it was chosen not to expose the full MILP algorithm here, as it may be found in (Kamerling et al., 2021). Nonetheless, a summary is given here, as well as the thermocline specific approach. The cost function is the boiler use. The implemented constraints represent the constraints of the system.

This MILP algorithm can be considered as a *water-flow* MILP, as opposed to *energy-flow* MILP. (Moretti et al., 2021) summarizes well the difference: the second approach only considers energy balances without taking into account temperatures and mass flow rates, whereas the first one directly implements mass flows and temperatures; the non-linear term formed by the product of mass flow rate and temperature is linearized through the use of binary variables and a discretization of the temperature levels, as is described below.

The main subtlety lies in the pre-calculation of the solar field flows at discretized output temperatures, and the use of binary variables for the choice of production. Since inertia must be taken into account, a binary variable spanning two time slots is considered:

$$z_{h,i,j} = \begin{cases} 1 \text{ if } T_{SF,h} = T_i \text{ and } T_{SF,h-1} = T_j \\ 0 \text{ else} \end{cases}$$
, with T_i and T_j in the set of discretized variables.

The mass stored by the algorithm must not exceed a maximum mass, which we have defined by $M_{max} = \rho_{HTF}(T_{process}) * V_{tank}$, in order not to overpass a threshold temperature at the bottom of the storage, and not to send a too hot fluid in the solar field (see section 3.2.3.).

The notion of bypass flow (\dot{m}_{aux}) is necessary because of the MILP algorithm: the thermal losses in the tank must be taken into account to get closer to the real operation, which forces to add in the cost function a cost proportional to the mass in the storage (virtual in the case of a thermocline storage). Therefore, this mass cannot be negative, even though it is virtual. Therefore, it is necessary to define an exit gate to the MILP to respect the constraint of a positive mass.

This is written by the following constraints: $\forall h, 0 \le M_{st,h} \le M_{max}$ et $M_{st,h+1} = M_{st,h} + 3600.* (\dot{m}_{SF} + \dot{m}_{aux} - \dot{m}_{demand}).$

The mass present in the storage at the beginning of the MILP calculation (i.e., at midnight), was calculated as follows: $M_0 = M_{max} * \tau$, with τ the charge percentage of the storage defined in 3.2.4.

4.2. Control approach 1 (CA1)

This control approach tries to always operate at the process temperature. It therefore heats the solar field in the morning and then switches it on. If the mass flow rate producible at the demand temperature is higher than the demand mass flow rate, the excess is stored. If it is lower, the storage is emptied; if the storage is empty, the bypass flow m_{aux} allows to complete the need. If the storage is full, in the sense that the overall mass injected into the thermocline storage is greater than M_{max} , the solar field is defocused. The mass present in the storage at the beginning of the simulation is calculated in the same way as above.

5. Case Study

A case study is presented here: production of chemical and intermediate products at Tarragona (Spain). The demand is considered constant at 280°C, with a flow rate of 20 kg/s. The return temperature is assumed to be 50°C. This corresponds to a power demand of 11.4 MW, and a daily heat demand of 273.6 MWh. The storage is designed to deliver heat for 6 hours at nominal rate and process temperature. The meteorological data are from PVGIS (EU SCIENCE HUB, 2017). The number of discretization of the outlet temperature of the solar field is 8. The yearly simulation time is of 23 minutes on a computer with a 3GHz processor and 32Go of RAM.

5.1. Design

The design of the plant is as follows:

- A loop structure consisting of a "rectangle" of PTC: 10 in series and 5 in parallel, followed by a line of LFR: 8 in series, 1 in parallel. This gives an aperture area for a loop of 519m².
- 67 loops, for a total aperture area of 34.773m²
- A storage volume of $256m^3$, which makes an HTF volume of $69m^3$ and a solid volume of $187m^3$, or 56.8t of HTF and 467t of solids, for a storage capacity between $T_{return} = 50^{\circ}C$ and $T_{process} = 280^{\circ}C$ of $\Delta E = E_{max} E_{min} = 34.18 MWh$

5.2. Hourly results

In this section, hourly results are commented. These results correspond to February 25th and 26th, and June 19th and 20th, to compare two different solar conditions.



Fig. 6. Hourly results of the simulation on the 25th and 26th of February

Fig. 6.a presents the DNI in W/m² which is intermittent on the 25th and closer to a clear-sky day on the 26th; Fig 6.b. shows the power on the receiver, in $W/m_{aperture}^2$; Fig.6.c. gives the ambient temperature in °C; Fig. 6.d. shows the demand mass flow rate in kg/s; Fig.6.e. presents the mass flow rate from both control strategies, i.e. MILP and CA1; Fig.6.f. presents the outlet temperature of the Solar Field; Fig.6.g. presents the stored energy in %; Fig.6.h. presents the outlet temperature of the storage; Fig.6.i. presents the heat losses in the solar field; Fig.6.j. shows the heat collected by the solar field; Fig.6.k. shows the heat produced by the boiler; Fig.6.l. presents the defocused energy in the Solar Field.

Fig.6.e. shows that the mass flow rate is increased in MILP strategy, whereas its outlet temperature is decreased. This explains why the heat losses are lower in the Solar Field, as can be seen on Fig.6.i, as compared to CA1. Fig.6.k. shows that the MILP algorithm smooths the boiler energy need, which is a side effect (i.e., it was not implemented straightforward) that might be interesting if the variability of the efficiency of the boiler with the thermal load is taken into account. Figures 6.g. et 6.h. show that the MILP makes a better use of the storage as compared to CA1.



Fig. 7. Hourly results of the simulation on the $19^{\rm th}$ and $20^{\rm th}$ of June

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Fig.7. presents the same variables as in Fig.6, but at a different time of the year, in which irradiation and optical efficiency are higher. Here, the main contribution of the MILP algorithm as compared to CA1 appears in the period of the defocused energy: the MILP algorithm prefers to defocuse in the morning, and then fills the storage to pass the night. Indeed, the MILP algorithm lowers the heat losses of the storage. The maximum filling of the storage is explained by the mass threshold (or temperature threshold) beyond which the storage cannot be charged anymore.

Discussion

We can see in Figure 6.h. that the outlet temperature of the storage increases and then decreases: the thermocline is not really a thermocline, the hot/cold zone separation is not clear.

In electricity production, keeping a constant inlet temperature to the turbine is of primary importance, for which it is much more interesting to keep a high quality thermocline. For SHIP with hybridization and a large difference in ΔT between the return and process temperature, it is shown here that it may be advantageous not to favour the quality of the thermocline but rather the quantity of stored energy. There is indeed a loss in exergy because of mixing, but the number of calories from the solar field being higher and the boiler completing the exergy loss most of the time; it appears to be in the end favourable.

Nevertheless, if the SF inlet temperature is close to the SF outlet temperature, the impact of the optimization on the temperature is very small; moreover, the objective in this case should be to keep a thermocline in order to have access to the desired storage temperature. It is highly likely that a parallel architecture of the boiler is more interesting.

5.2. Yearly results

In this section, monthly results are presented over the year.





The Solar Fraction (SF_a , Fig.8.a.) is calculated as $SF_a = 1 - \frac{Q_{boller}}{Q_{demand}}$, with Q_{boiler} the heat from the boiler for the month, and Q_{demand} the heat demand during the month. The average charge percentage (Fig.8.b.) is calculated as the hourly average of the charge percentage. The monthly heat losses of the solar field (Fig.8.c.) correspond to the sum of the thermal losses when the solar field is operating. The monthly defocused energy (Fig.8.d.) correspond to the sum of the defocused energy.

The annual solar fraction of the MILP is 30.9% and that of the CA1 approach is 28.5%. During the summer, the two models behave differently: in fact, the MILP prefers to defocus in the morning and to fill the storage later, thus minimizing the thermal losses in the storage. This is why more energy is defocused by the MILP while keeping a higher solar fraction. In winter, the difference is explained by the difference in thermal losses.

6. Conclusion

This paper presented the results of a MILP algorithm applied to temperature optimization in a solar field with thermocline storage for industrial process heat. This optimization showed a 2.5% -point increase in the solar fraction as compared to a control trying to reach the process temperature as soon as possible.

Despite the risk of affecting stratification, varying the temperature of the storage inlet, has shown to be interesting in the case of hybridization with a high temperature difference between the return temperature and the process temperature. The use of the storage is maximized by the MILP algorithm, and it is interesting, in the case presented here, not to respect the order imposed by the stratification, because the storage is emptied by the constant demand all night long.

These optimization results seem very interesting, but limited to cases of large temperature difference between the input and the output, which opens a range of optimization. Another dimension of freedom can be found in the case of an industrial site with different heat requirements, and different production sites, approaching the notion of Total Site Analysis. This will be investigated in future works.

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Evaluation of a solar concentrating photovoltaic thermal collector (CPVT) in a dairy and swine farm in Europe

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Abstract

The use of CPVT collectors in combination with other renewable energy sources (RES) has been evaluated to develop market integrated, cost-effective and case sensitive RES solutions dairy and swine farms in view of fossilfree livestock farming practices. Electrical and thermal energy demands have been analyzed for the LVAT-ATB dairy farm in Germany, and for the ILVO swine farm in Belgium. The swine farm consumes more heat than electricity for pig raising while the dairy farm consumes more heat than electricity for milk production. A CPVT collector produced and tested by Solarus has been used to model the thermal and electrical performance output for each of the farms. Taking into consideration the demands of the farms, the use of the CPVT in a fossil-free energy system for the farm has been evaluated. For the swine farm it was suggested to make use of the higher efficiencies of the CPVT when operating at low temperatures at a mean temperature (Tm) of 20°C, to preheat grid water by 10-20°C and using to obtain the required temperatures for hot water and space heating. The specific annual thermal output of the CPVT at ILVO is 436.1 kWh/m². At the LVAT dairy farm, it is suggested to use the CPVT collectors to lift the temperature of the pre-heated water recovered from the milk coolers (40°C) by 10-15°C, running at a mean temperature (Tm) of 45°C. The specific annual thermal output of the CPVT at this Tm LVAT is 375.5 kWh/m². The remaining temperature difference can be supplied by an e-boiler. Running at the lowest mean temperature possible maximizes the thermal efficiency of the solar system.

Keywords: RES4Live project, CPVT Systems, Concentrating Photovoltaic-Thermal, Livestock Farms, Fossil-free Farming, Energy use of livestock farms

1. Introduction

Fossil fuel use in the agricultural domain has negative effects becoming a major source of greenhouse gas (GHG) emissions, with significant contributions to global climate change and the risk of food security (Dubois et al., 2017). The proportion of direct energy used from the total primary energy consumption in agriculture in the EU is estimated at 61% and largely varies for the specific activity (Blázquez et al., 2021). One of the most energy consuming sub-sectors of agriculture is intensive livestock that is mainly based on fossil fuels use representing about 45% of the total energy demand in the agricultural sector (Dumont et al., 2017). Both electricity and thermal energy is required to cover strongly diversified energy demand, such as cooling-heating of the indoor livestock buildings environment, running of equipment and tractors, lighting, and ventilation systems.

Dairy farming is one of the most energy- and emission-intensive industrial sectors and offers noteworthy opportunities for displacing conventional fossil-fuel consumption both in terms of cost saving and decarbonization. The main energy demands in dairy farms include electricity for pumps, refrigeration, storage, control, separation, lighting, etc., and thermal energy for pasteurization, evaporation, drying, cleaning, etc. The required temperature of thermal energy ranges from 20°C to 200°C, depending on the processes. Typically, low-temperature heat below 80°C is used for thermalization, pasteurization, cleaning, preheating, concentration, etc., and higher-temperature heat at around 110°C-180°C are required for sterilization, ultra-high temperature processing, drying, etc. (Ramos et al., 2017).

(Wallerand et al., 2018) performed an optimization of a solar-assisted energy supply system for a dairy farm, which integrated flat plate collectors, photovoltaic (PV) modules, high-concentration PV-thermal (PVT) collectors, and heat pumps into the existing natural gas and grid-electricity based system. The authors

demonstrated that the integration of solar technologies, in combination with heat recovery and heat pumping, can reduce the CO2-equivalent emissions by 65 to 75%. They also concluded that investment in solar energy for such applications can be economically and environmentally attractive for dairy farms if solar energy is optimally integrated and utilized.

In the context of pig farming productivity, the conditions of the inside room are essential and highly influence the correct animal's growth. Nursery pigs are susceptible to low temperatures and hence, a significant proportion of the global costs associated with pig farming is for heating to achieve a comfortable temperature. In intensive breeding farms, for maintaining an adequate thermal environment, fossil fuels and electricity are the principal energy sources usually adopted. In this way, interventions on animal housing are required with the aim of reducing the energy demand and increasing the efficiency of the climatization systems. Strategies are then focused on the use of alternative energy sources as the renewable ones. In this regard, geothermal heat pump or PVT systems represent a potential improvement both in energy consumption and indoor air quality (Blázquez et al., 2021). Furthermore, the economic sustainability of agricultural production is a crucial concern for most farmers, especially for pig producers who face dynamic changes in the market (Malak-Rawlikowska et al., 2021).

A study by (Menardo et al., 2013) shows the importance of heating usage in northern parts of Europe such as Germany and Belgium where solar applications can bring a useful contribution to the large heating needs in the north. The study specifies that the annual energy demand of greenhouse production is $220-320 \text{ MJ/m}^2$ of the cultivated area in Southern Europe (including Italy, Southern France, and Greece), while this value is up to $3,600 \text{ MJ/m}^2$ in North European countries (Poland, Germany, and Netherlands).

A photovoltaic thermal (PVT) collector is able to generate electricity and heat from the same area and is a single unit formed by a combination of photovoltaic (PV) and solar thermal technologies (Zhang et al., 2012). PVT collectors integrate photovoltaic and thermal solar energy conversion in a single device and thereby reach high yields per area (about 30% higher than having separate PV and solar thermal collectors with the same total surface area) (Ramos et al., 2017; Zenhäusern et al., 2017). Concentrating hybrid photovoltaic thermal collectors (CPVT) provide a promising option to effectively contribute to the high intensity energy use of livestock farms. With declining costs and improvement of reliability and performance of key renewable energy sources (RES) technologies, the opportunities for farmers and specifically for livestock producers to engage in RES production are increasing. However, this large portfolio of options also creates complex questions, because the potential, performance and impacts of RES technologies depend on the local climate and desirable indoor conditions, size and type of farm, management techniques, degree of mechanisation, and socio-economic factors. Furthermore, very few case studies have been conducted to evaluate PVT systems in agriculture sector (Gorjian et al., 2020; Singh et al., 2018; Tiwari and Tiwari, 2016).

The integration of a concentrating PVT with a greenhouse was evaluated by (Hussain et al., 2016) from technical and economic points of view. In their study, two CPVT modules, one with and the other without a glass-reinforced plastic envelope, were used to supply energy to the considered greenhouse. Results indicated better efficiency for the glass reinforced CPVT with reduced heat loss compared to the other. It was also found that the integration of a CPVT module with a greenhouse to meet the heat demand of the greenhouse causes a remarkable Discounted Payback Period and Life Cycle Saving.

In this paper, one dairy farm (LVAT-ATB) and one swine farm (ILVO) have been selected as case studies to evaluate the use and integration of solar CPVTs in the energy usage of the farms. Special attention has been taken in the thermal part of the energy usage and production, as in both farms the consumption is high. The heating and electricity demands have been analyzed for both cases. Then, the performance of a CPVT solar collector has been calculated for both locations. An evaluation on the integration of the CPVT into the heating processes of the farm was done, also considering its integration with other renewable energy sources (RES). Finally, an integration point of the solar thermal energy is proposed, as well as the operating conditions of the solar system. Both farms are chosen to be from a similar climate to minimize the variation in solar collector performance due to different solar radiation values. The average solar radiation over a year measured at the ILVO farm in Melle, Belgium is 83.9 kWh/m², while at LVAT in Potsdam, Germany it is 84.5kWh/m². It is important to understand that the electrical and thermal energy demand have been assessed for milk production (LVAT-ATB), and the raising of pigs (ILVO) as end products.

2. Swine farm at Vaarkenscampus EV ILVO (Belgium)

The Swine farm (Figure 1) is managed by EV ILVO, UGENT and HoGent for research and educational purposes alongside normal commercial production. It is a farrow-to-finish pig farm with place at any moment for 105 sows, 600 piglets and 750 fattening pigs. The total building area is 2,500 m² and contains mainly concrete and insulation with polypropylene panels dividing the compartments and partially slatted concrete floors above the manure pits.



Fig. 1. ILVO swine farm in Belgium (top), and its floor plan (bottom)

Heating at the ILVO swine farm is currently provided year-round by a 60 kW gas boiler with a LPG energy consumption of 220 MWh/year. On top of this, thermal lamps are used to heat new-born piglets specifically. This is a characteristic of a swine farm as new-born piglets must remain at a temperature of 35-37°C, while the sow should remain at room temperature. Currently at the ILVO farm, the LPG gas boiler supplies hot water at 70°C. This is delivered to the air heating channels for the weaned and fattening pigs' compartments, as well as for domestic hot water. This hot water is reduced to 40°C for the floor heating system used for the new-born piglets and weaned piglets compartments. The multitude of delivery systems of heat depending on the stage of production is summarized in Table 1.

Stage of production	Heating required	Heating delivery
New-born piglets	35-37 °C first days after birth	Floor heating (water at 40°C) and thermal lamps
Weaned piglets	28°C gradually decreasing to 25°C during 4 weeks	Floor heating (water at 40°C) and air heating (from water at 70°C)
Fattening Pigs	20-25°C	Air heating and use of gas cannon at start-up
Sows	No need for extra heating (18-23°C)	

Tab. 1: Summary of heating requirements of the ILVO Farm

As the thermal lamps deliver location specific heating, it will be difficult to replace this using solar heating for the case of this specific farm. Thus, only the heating requirements from the LPG boiler will be considered. Using the heating schedules of the farm, and energy flow measurements recorded over a week in October 2020, the breakdown of thermal energy demand of the farm over a year was estimated as shown in Figure 2. Floor heating is constant at 7200 kWh/month. Domestic hot water is on average over the year constant at 992 kWh/month. Space heating fluctuates based on the outdoor temperature and between June and September, almost no energy is used for space heating additional to floor heating. However, space heating does take up the most energy overall during a year.



Fig. 2. Estimated thermal energy demand for hot water at ILVO swine farm.

The overall average electricity demand of the farm is 110 MWh/year. The main electricity consumption comes from the 32 thermal lamps that are used to heat the newborn piglets. Otherwise, there are 200 LED lights, and

several electric pumps for the feed and pressure cleaning. There are also 6 pressure fans and 8 DC fans for ventilation in the barn. The monthly electricity consumption over the year is constant as shown in Figure 3. The thermal lamps are needed all year round, however the ventilation is only needed during the summer which explains the slight increase in electricity usage over the summer months.

Monthly Electricity Consumption for 2020 at ILVO 12000 fotal electricity consumption (kWh) 10000 8000 6000 4000 2000 0 JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC Month of the year



Figure 4 shows a daily fluke electricity analysis of the electricity demand over a day in November 2020. This shows that the electricity consumed in generally during the day between 5 am and 6 pm.



Fig. 4. Fluke Electricity analysis of the electricity demand over a day at the ILVO swine farm in Belgium

3. Energy Usage from the Dairy Farm at LVAT-ATB (Germany)

The LVAT-ATB dairy farm in Potsdam, Germany includes three barns for milk production with a total area of $3,950 \text{ m}^2$, with an overall number of 445 cows and calves. Barn A houses 150 cows on an area of 2240 m², Barn B houses 70 cows on an area of 630 m², and barn C houses 140 cows on an area of 1080 m² (Figure 5). All barns are naturally ventilated, but there are ventilators with fans to provide fresh air and cooling in warmer days. An average energy consumption of the farm are presented next:



Fig. 5. Dairy farm at LVAT-ATB in Germany

For heating the working areas related to milk production (space heating), the farm has a LPG consumption on average of 30000 kWh/year. A unique feature in dairy farms in terms of energy is that they require a milk cooler to store the produced milk until it leaves the farm. In the described farm, there are two milk coolers which each recovers heat to supply to the heating processes of the farm. As seen in Figure 6, each milk cooler supplies heat to a different heat demand point. For the purposes of this paper, the two streams have been divided into cycle A and cycle B. Cycle A uses heat from the interior milk cooler to supply the automatic milking system (AMS) of the farm. The AMS uses any recovered heat and internally upgrades this heat electrically to 83 °C. Cycle B uses heat from the exterior milk cooler to supply intermediary heat to the e-boiler which provides domestic hot water at 80 °C for warm water taps and cleaning the milking parlors and tanks.



Fig. 6. Summary of the current situation of dairy farm at LVAT-ATB in Germany.

Figure 7 shows the estimated thermal energy demand at LVAT-ATB. In cycle A (Blue), cleaning and disinfection of the milking robot is performed 3 times a day (every 8 hours) by hot water. In addition, a general cleaning is also performed every day in this cycle. Therefore, the total demand of hot water at 68°C in cycle A is 400 L per day. In cycle B, hot water is used for rinsing the inside and outside milk tanks (every two days between 7 and 8 pm), milking parlor (7am and 4.30 pm) and buckets. In addition, this cycle is also used for hot water taps. The total demand of hot water at 80°C in cycle B is 1500 L per day. The average monthly thermal energy demand of cycle A and cycle B in LVAT-ATB are 771 kWh and 3577 kWh respectively. The farm is operational all year round with a constant energy need. Thus, the average monthly contribution of annual heating for both cycles is 8.3%. The total estimated annual thermal energy demand for milk production (excluding space heating) at LVAT-ATB is 52197 kWh, where cycle A and cycle B require 9249 kWh and 42930 kWh respectively.



Fig. 7. Estimated thermal energy demand breakdown and percentage of contribution to annual demand for milk production at LVAT-ATB dairy farm.

Figure 8 shows an overview of the estimated daily electricity demand at LVAT-ATB. The pie chart illustrates the share of annual electricity demand, giving the percentages for each application in LVAT-ATB. The electricity demand for the ventilation fans is 170 kWh/day in summer times. In winter times under frosty conditions, the troughs need heating with an electricity consumption of 118 kWh/day. The cows are milked with automatic milking systems, consuming electricity of 152 kWh/day. The milk needs to be cooled constantly over the year with an electric demand of about 115 kWh/day. The lighting of the barns demands around 177 kWh/day constantly over the year. For manure management, electricity needs are 240 kWh/day. Overall, the LVAT-ATB farm has an electricity consumption of about 201000 kWh/year for milk production. For heating the working areas related to milk production, 30000 kWh/year is needed.



Fig. 8. Daily electricity demand breakdown in summer and share of annual electricity demand for each application at LVAT-ATB

4. The Solarus PowerCollector CPVT

CPVT is a concentrating, hybrid solar photovoltaic and solar thermal collector (CPVT), which generates both electricity (from PV) and heat (from the Thermal part) from the same gross area. The collector reflects and concentrates the incoming sunlight, from its reflective mirrors to the bottom side of a (horizontally placed) PVT receiver. When applied in the right system design, PVT provides energy yields per m² about 30% higher than having separate PV and solar thermal collectors with the same total surface area (Ramos et al., 2017).

The Solarus bi-facial CPVT collector has been selected for this study as a model CPVT to determine energy production values at the two different farms. The electrical performance of the Solarus CPVT collector was characterized according to IEC 62108 (2007) while the thermal performance was characterized according to ISO 9806:2017 (by Steady-state (SS) test methods). Results from performance assessment in the Solar Laboratory of University of Gävle showed that the electrical peak efficiency of 11.5% and 11.2% ($R^2 = 0.999$) has been achieved for the bottom and top trough (respectively) for a module temperature of 25 °C. The steady electrical peak efficiency for higher temperatures, gives a temperature dependence coefficient of around 0.49 %/°C. Regarding

the optical efficiency η_0 , a value of 58.2 % (divided in 47.0 %_{th} and 11.2 %_{elect}, $\mathbf{R}^2 = 0.997$) has been obtained per aperture area. The technical specifications of this collectors is presented in Table 2.

Company	Technology	Size [m ²]		PV Specifications		Thermal Specifications			
		Gross	Aperture	Cell Type	Power Peak [W]	Eff. [%]	ηο	a1 [W/m².k]	a2 [W/m ² .k ²]
Solarus	C-PVT	2.57	2.31	Mono	260	11	0.47	4.05	0.003

Tab. 2. Solar PowerCollector CPVT characteristics.

The efficiencies presented in the following sections for each farm at the corresponding mean temperature (T_m) were obtained using the formula presented in Eq.1. Subsequently, the specific yield was obtained accounting for the monthly direct normal irradiance values as in Eq.2.

$$\eta_{coll} = \eta_0 - a_1 \frac{T_m - T_{amb}}{DNI} - a_2 \frac{(T_m - T_{amb})^2}{DNI}$$
(Eq.1)

Where η_{coll} is the collector efficiency, DNI is direct normal irradiance $[W/m^2]$, η_0 is peak optical efficiency, a_1 is linear heat loss coefficient $[W/m^2K]$, a_2 is quadratic heat loss coefficient $[W/m^2K^2]$, T_m is mean temperature [°C] and T_{amb} is ambient temperature [°C] (Eck et al., 2014; Janotte et al., 2014; Osório and Carvalho, 2014).

$$STP = DNI * \eta_{coll}$$
(Eq.2)

where STP the specific thermal production in [kWh/m²], DNI in [kWh/m²] and collector efficiency η_{coll} as calculated in Eq.1.

5. Use of CPVT collectors at a Swine Farm

The analysis of thermal requirements of the ILVO swine farm is used to better understand the effect of using solar technology in supplying the farm with heat and electricity. The specifications of the Solarus CPVT and the location of the farm have been used to estimate the energy production in using the Solarus CPVT as a model CPVT collector. In this analysis, the thermal production of the CPVT has been prioritized over the electrical production, which will be supplied as a by-product.

The total annual thermal demand of the swine farm (excluding thermal lamps) is estimated at 198 MWh, when assuming a gas boiler at 90% efficiency with a total annual LPG consumption of 220 MWh. To meet this annual demand only using the Solarus CPVT, it was calculated that at least 480 m² of collector aperture area is needed to fulfill this demand for an output temperature of 70°C. Furthermore, as seen in Figure 9, most of the solar thermal production is made during the summer months, while most of the thermal demand is during the winter months.



Comparison of thermal energy demand and thermal energy production of 480 sqm of Solarus CPVT at ILVO farm

Fig. 9. Thermal energy demand (yellow) and thermal energy production of 480 sqm Solarus CPVT (orange) at the ILVO swine farm To use the excess heat produced during the summer for use during the winter, a large seasonal storage is required. This scenario is not practical as this would incur very high costs. Furthermore, even though space is available at

the farm, the large solar field will also incur a very high cost. From a technical point of view, running a solar thermal system at high temperatures, in this case from ca. 9° C (average grid water temperature) to 70° C will result in high thermal losses and drastically reduce efficiency during the winter. Figure 10 shows the difference in efficiency and specific thermal production of the collector running at mean temperature Tm=40°C and Tm=20°C. The efficiency at lower running temperature is much greater and will allow for more thermal output, thus decreasing the cost per thermal energy produced. Overproduction, which is the case here during the summer is also not recommended unless a suitable thermal storage is available. If there is excess thermal production in the solar system, there is a risk of the collectors shutting down as it reaches its maximum operating temperature. If there are no safety measures in place, this could lead to the breakdown of the collectors and system. Thus, it is proposed to run the system at lower temperatures, only lifting the temperature by ca. 10-20°C above grid temperature. In this case the specific annual thermal output of the CPVT at ILVO is 436.1 kWh/m².





For the above reasons, the system proposed for the ILVO swine farm when using solar PVT collectors or CPVTs, is to use the collectors at lower temperatures at $Tm=20^{\circ}C$ to maximize efficiency and integrate the collectors with heat pumps that will deliver the final temperature requirements. In this case the solar collectors will produce heat to lift the COP of the heat pumps, increasing their efficiency, and decreasing their electricity load. One heat pump will supply heat for the floor heating system which runs constantly at 40°C. The other high pump will run at higher temperature to supply heat at 70°C for domestic hot water and the air heating channels. Figure 11 shows an overview of the proposed integrated system. The sizing of the solar collector system will then depend on the specifications of the heat pump.



Fig. 11. Overview of proposed system integrating CPVT collectors at the ILVO swine farm in Belgium

The specific annual electrical production of the Solarus CPVT at the ILVO farm is 111 kWh/m^2 . To meet the annual electrical demand of 110 MWh, 994 m^2 of aperture area is required. However, as the case of most PVT designs, the remaining electrical demand must be met from other sources such as PV or from the electricity grid.

6. Use of CPVT collectors at a Diary Farm

In this analysis, as with the case with the swine farm, the thermal production of the CPVT has been prioritized over the electrical production, which will be supplied as a by-product. As mentioned in previous sections, the dairy farm has the advantage of a milk cooler, where heat can be recovered from. Since the energy demand of cycle B is greater than cycle A, it was suggested to intervene in the cycle B process. To use the heat recovery of the milk coolers and reduce the electricity consumption of the e-boiler, it was decided to keep this system as an integral part of the energy source of the farm and integrate the solar system in cycle B between the heat recovery tank and the e-boiler. Thus, a system is proposed to use the thermal heat from the solar system to lift the temperature at the outlet of the buffer tank from 40°C to 50-55°C and use the milk cooler heat recovery as a quasiheat pump. The last increase in needed temperature (from 50-55°C to 80°C) at cycle B of LVAT-ATB will be supplied by e-boiler (trough grid electricity). The proposed system is shown in Figure 12.



Fig. 12. Overview of the proposed system with (C)PVT collectors at the LVAT-ATB dairy farm in Germany.

With use of the PVT system in cycle B, the temperature available to the E-Boiler would be increased to 55°C and would require less energy to meet the required temperature of this cycle. In this design electric boilers would ensure any additional heating demand in the case of minimal solar radiation by the help the electricity from the grid. Additional PV panels would be needed to meet all the electrical needs of the farm.

The total estimated annual thermal energy demand for milk production (excluding space heating) at LVAT-ATB is 52 197 kWh, where cycle A and cycle B (c.f. figure 6) require 9 249 kWh and 42 930 kWh respectively. To meet the heating demand (42 930 kWh) after the heat recovery system in cycle B, the CPVT collectors would need to supply the required amount of hot water at 80°C, effectively replacing the e-boiler. To do this, the total aperture area of the Solarus CPVT needed would be 140 m². This is a possible option considering the available roof space of the farm. However, as with the case at the ILVO farm, running at high temperatures would not be an efficient option, and in the case of low solar radiation, a backup heater is suggested. The safest option would be to run the solar system at the lowest possible temperature for highest efficiency, lifting the temperature from 40°C to 50-55°C, and use the e-boiler to heat up to the required temperature. Using the Solarus PVT at a mean temperature (Tm) of 45°C, the specific annual thermal output at LVAT is 375.5 kWh/m². The monthly thermal production over a year and the change in efficiency of the collector across the year is shown in Figure 13.



Solarus CPVT thermal performance at operating temperature Tm=45°C at LVAT farm

Fig. 13. Thermal performance of Solarus CPVT at Tm=45°C at the LVAT farm in Germany

The specific annual electrical production of the Solarus CPVT at the LVAT farm is 142 kWh/m². To meet the annual electrical demand of 201 MWh, 1416 m² of aperture area is required. Again, as the case of most PVT designs, the remaining electrical demand must be met from other sources such as PV or from the electricity grid.

7. Conclusion

The case study analysis of the energy usage of the swine farm at ILVO, Belgium, and the dairy farm at LVAT-ATB, Germany, shows the difference in heating and electrical demand of the two types of farms. The swine farm consumes more heat than electricity for pig raising while the dairy farm consumes more heat than electricity for milk production. This is partly due to the high electricity consumers of the automatic milking system in the diary farm and the year-round heating needs for raising piglets in the swine farm. For the swine farm it is suggested to make use of the higher efficiencies of the CPVT when operating at low temperatures at a mean temperature (Tm) of 20°C, to preheat grid water by 10-20°C and using two types of heat pumps to obtain the required temperatures for hot water and space heating. This is suggested to be a more economical scenario than installing CPVT collectors to cover the entire demand where most of the heat generated in the summer will not be used. The specific annual thermal output of the CPVT at ILVO is 436.1 kWh/m². The dairy farm has the advantage of possessing a milk cooler where heat can be recovered from. This is the case at the LVAT farm. It is suggested to use the CPVT collectors to lift the temperature of the pre-heated water (40°C) by 10-15°C, running at a mean temperature (Tm) of 45°C. The specific annual thermal output of the CPVT at this Tm LVAT is 375.5 kWh/m². The remaining temperature difference can be supplied by an e-boiler. Running at the lowest mean temperature possible maximizes the thermal efficiency of the solar system. Further modelling and simulations need to be done to determine the optimal integration temperatures of both systems coupled with the heat recovery storage and heat pumps, both technically and economically. Further study should also be made in the cost benefit of the size of such a solar system in comparison with heating with electricity. In the future the levelized cost of heat for solar thermal and (C)PVT applications is likely to decline as electricity and fossil-fuel prices rise.

8. Acknowledgements

This work has been performed as part of the RES4LIVE project (Energy Smart Livestock Farming towards Zero Fossil Fuel Consumption) and has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101000785. The authors would like to give particular thanks to Razif Kunjumon, and other members of MG Sustainable Engineering AB for their contribution to the paper and project. Finally, the autors would like to express their gratitude to the project consortium of RES4LIVE, and to the EU commission, without which we would not be able to be part of this important and exciting innovation action contributing to the de-fossilization of livestock farms.

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Energetic and Economic Analysis of a Solar Assisted Heat Pump for Pasteurization Process

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Abstract

In the present paper, the energetic and economic analysis of a solar-assisted heat pump for an industrial pasteurization process is investigated. The considered system consists of thermal energy storage, a water-to-water heat pump and a solar field made up of both photovoltaic-thermal collectors and evacuated tube collectors. A mathematical model of each component of the system is built and validated, while the overall model of the system is built with a bottom-up approach. The energetic and economic analysis is performed on a yearly basis varying the storage size and the solar field size and considering a boiler-only scenario as the reference system. The results show that, from the energetic point of view, the best system could provide up to 90% of the energy required by the process and, consequently, significantly reduce auxiliary boiler consumption. On the other side, from an economic point of view, the best solution provides a minimum payback time approximately equal to 8 years with 14.4% internal rate of return.

Keywords: Economic analysis, Energetic analysis, Pasteurization, Solar assisted heat pump

1. Introduction

According to Eurostat (Eurostat, 2021), in 2019 the industrial sector is responsible of 25.6% of final energy consumption in Europe. Five sectors, i.e. chemical, non-metallic minerals, paper, food and steel industries, accounts for about two thirds of the total energy consumption in industry (Papapetrou et al., 2018) and both heat and electricity are energy carriers. Electricity is widely used in motors, compressors and lightning, while the process heat is required in a wide range of temperatures, starting from about 100 °C in food and textiles industries to more than 500 °C in metal processing industries.

Among the industrial process in the food industry, the pasteurization process is considered a low temperature process since it requires heat at temperature in the range 65 °C – 120 °C (Brückner et al., 2015). Although this low-mid temperature heat is typically supplied by a boiler, an improvement of the overall pasteurization process energetic performance could be achieved considering heat pumps. Indeed, a lot of research efforts are currently being put in mid-high temperature heat pump development (Arpagaus et al., 2018, Van de Bor et al., 2013) due to the superior energetic and environmental performance of this technology.

An even more interesting alternative to the conventional boiler could be the solar assisted heat pump (SAHP) system that relies upon the integration of a solar field with a heat pump in which the hot water at solar field outlet is used as cold heat source in the heat pump evaporator. In this way it is possible to exploit solar radiation more efficiently, since the water temperature may be significantly lower than the temperature required by the process, improving both the heat pump and the solar collector efficiencies. In the open literature, a lot of experimental or numerical analyses SAHP systems are carried out demonstrating the superior performance of this integrated system with respect to traditional systems such as boiler or conventional heat pump (Kamel et al., 2015, Mohanraj et al. 2018, Lazzarin, 2020, Simonetti et al. 2019, 2020). However, all the available studies deal with SAHP systems at residential scale and there is lack of analysis of their application to industrial processes.

Therefore, in the present work an energetic and economic analysis of the use of mid temperature SAHP system in a pasteurization process is carried out with the aim of demonstrating its feasibility in an industrial scenario.

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2. System modelling

The system under investigation is a solar assisted heat pump system used to supply heat to a pasteurization process. The layout of the system is shown in Fig. 1 and, besides the pasteurization process itself, it consists of:

• A heat pump that supplies heat to the pasteurization process.

• A solar field where both photovoltaic/thermal collectors (PV/T) and evacuated tube collectors (ETC) are considered. The PV/Ts are used to produce low temperature heat which, in turn, is used as cold heat source in the heat pump evaporator whereas the hot water at ETCs may be exploited either in the heat pump evaporator or in the pasteurization process depending on its temperature.

• A heat storage which stores the system excess heat allowing for larger solar source exploitation.

• An auxiliary boiler that is used only when the SAHP system, together with the heat storage, cannot provide the heat required by the pasteurization process (low solar radiation and/or low amount of heat in the storage). The auxiliary boiler is aimed to allow continuous system operation during the whole year.



Fig. 1: Layout of the solar assisted heat pump system for pasteurization process

The model of the system is built starting from the model of each component as detailed in the next sections.

2.1 Heat pump

The heat pump considered in this work is a water-to-water heat pump system working with carbon dioxide in transcritical mode. The refrigerant properties are calculated using Refprop 9.1 (Lemmon et al., 2013) whereas the layout of the heat pump is shown in Fig. 2.



Fig. 2: Layout of the heat pump

The model of the heat pump is a steady-state model built with a bottom-up approach. The model of each component of the heat pump is first realized and then the overall heat pump model is built assembling them together.

The compressor considered in the present work is a variable speed reciprocating compressor. The compressor is modelled using the polynomial functional form provided by the manufacturer that allows for the calculation of

refrigerant mass flow rate or compressor power as a function of evaporating temperature and gas cooler outlet pressure:

$$\dot{m} = a_1 + a_2 T_E + a_3 p_{0,GC} + a_4 T_E^2 + a_5 T_E p_{0,GC} + a_6 p_{0,GC}^2 + a_7 T_E^3 + a_8 T_E^2 p_{0,GC} + a_9 T_E p_{0,GC}^2 + a_{10} p_{0,GC}^3$$

$$(eq. 1)$$

$$\dot{W} = b_1 + b_2 T_E + b_3 p_{0,GC} + b_4 T_E^2 + b_5 T_E p_{0,GC} + b_6 p_{0,GC}^2 + b_7 T_E^3 + b_8 T_E^2 p_{0,GC} + b_9 T_E p_{0,GC}^2 + b_{10} p_{0,GC}^3$$

(eq. 2)

The 10 coefficients that appear in Eqs. (1-2) depend on the rotational frequency of the compressor shaft and are taken from the manufacturer's datasheet. Since the model is valid only for a refrigerant superheating at compressor suction equal to 10 K, the corrective action proposed by Dabiri and Rice (1981) is used to account for a different superheat. Finally, due to the heat pump application, the compressor is assumed to be adiabatic and, therefore, the following equation applies for the calculation of refrigerant enthalpy at compressor discharge:

$$h_{\text{DIS}} = h_{\text{SUC}} + \dot{W} / \dot{m} \tag{eq. 3}$$

The three heat exchangers are modelled using a finite volume approach. Each heat exchanger is divided in small slices and the amount of heat transferred between the hot and cold fluid in the small volume is calculated using the ϵ -NTU method according to the following equations:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{MAX}} = \frac{1 - exp[-NTU(1 - R^*)]}{1 - R^* exp[-NTU(1 - R^*)]}$$
(eq. 4)

$$\dot{Q} = \dot{m}_{H}c_{P,H}(T_{H,IN} - T_{H,OUT}) = \dot{m}_{C}c_{P,C}(T_{C,OUT} - T_{C,IN})$$
(eq. 5)

$$\dot{Q}_{MAX} = \min\left(\dot{m}_{H}c_{P,H},\dot{m}_{C}c_{P,C}\right)\left(T_{H,IN} - T_{C,IN}\right)$$
 (eq. 6)

$$R^* = \frac{\min(\dot{m}_H c_{P,H}, \dot{m}_C c_{P,C})(T_{H,IN} - T_{C,IN})}{\max(\dot{m}_H c_{P,H}, \dot{m}_C c_{P,C})(T_{H,IN} - T_{C,IN})}$$
(eq. 7)

$$NTU = \frac{UA}{\min(\dot{m}_{H}c_{P,H},\dot{m}_{C}c_{P,C})(T_{H,IN} - T_{C,IN})}$$
(eq. 8)

$$(UA)^{-1} = (h_{C,H}A)^{-1} + t_W(k_WA)^{-1} + (h_{C,C}A)^{-1}$$
(eq. 9)

The overall heat transfer rate is, then, the sum of the infinitesimal heat transfer rate at volume scale.

The correlation used for the calculation of the heat transfer coefficient are an in-house correlation for the single phase fluid (water in evaporator and gas cooler, carbon dioxide in gas cooler, internal heat exchanger and vapour zone in evaporator) whereas the correlation proposed by Longo et al. (2015) is used in the two-phase zone of the evaporator.

Finally, the back-pressure expansion valve is modelled considering an isenthalpic process and assuming that the valve is able to keep the gas cooler outlet pressure at the optimal value in any heat pump operating conditions.

2.2 Solar collectors

As stated, the solar collectors used in the present study are both photovoltaic/thermal collectors (PV/T) and evacuated tube collectors (ETC). For the sake of simplicity, and similarly to the heat pump model, the soalr collector models are steady-state too.

Considering the PV/Ts first, both an electrical model and a thermal model is needed. The electrical model used in the present work computes the electrical efficiency with the power coefficient approach (Zondag et al., 2003) assuming, for the sake of simplicity, that the PV cell temperature is 10 °C higher than the water average temperature:

$$\eta_{EL} = \eta_{EL,REF} \left[1 + \gamma_{PVT} \left(\overline{T}_W + 10 - T_{CELL,REF} \right) \right]$$
(eq. 10)

whereas the thermal model computes the thermal efficiency as a function of optical efficiency and thermal losses which, in turn, depends on the reduced temperature. Due to the low operating temperature of this collector, only the linear term is considered and, similarly to the electrical model, the water average temperature is used for the sake of simplicity:

$$\eta_{TH} = \eta_{OPT} - k_{1,PVT} \frac{(\bar{T}_W - T_A)}{g}$$
(eq. 11)

ETC collectors need only a thermal model which is very similar to that of PV/Ts. Indeed, again, the thermal model of ETC computes the thermal efficiency as a function of optical efficiency and thermal losses but the quadratic term is considered for this type of collector due to the higher operating temperatures:

$$\eta_{TH} = \eta_{OPT} - k_{1,ETC} \frac{(\bar{T}_W - T_A)}{G} - k_{2,ETC} \frac{(\bar{T}_W - T_A)^2}{G}$$
(eq. 12)

The constants that appear in eqs. (10-12) are taken from manufacturers' datasheets.

2.3 Heat storage, boiler and pumps

Finally, simple models are developed also for the heat storage, the auxiliary boiler and the pumps.

The heat storage is modelled as a perfectly stratified heat storage where the thermocline is adiabatic and has a thickness equal to zero. No mixing phenomena occur when water is injected to or extracted from it. The storage is assumed to be well insulated, therefore the heat loss to the environment is neglected.

The boiler is modelled as a constant efficiency thermal system. The boiler efficiency is chosen averaging the value reported in several manufacturers' datasheet.

Pumps are modelled in order to account for the pumping power in the overall system consumption. First, pressure drop in the evaporator or in the solar collectors is calculated using the following equation:

$$\Delta p = c_1 + c_2 \dot{v}_W + c_3 \dot{v}_W^2 \tag{eq. 13}$$

The constants that appear in eq. 13 are taken from manufacturers' datasheet (solar collectors) or are regressed using a best fitting procedure over manufacturer's performance data (brazed plate evaporator).

Once the pressure drop is calculated, the pumping power is computed according to eq. 14 in which the pump efficiency is taken from manufacturers' datasheet:

$$\dot{W}_{PUMP} = \frac{\dot{v}_W \Delta p}{\eta_{PUMP}} \tag{eq. 14}$$

3. Case study

As stated, the goal of the present study is to assess the energetic and economic performance of a SAHP for pasteurization process. With the aim of making the analysis as simple as possible, without loosing accuracy or consistency with a real pasteurization process, the pasteurization process is assumed to operate continuously, i.e. 24 hours a day and 7 days a week. Additionally, it is assumed that a water mass flow rate equal to $\dot{m}_W = 1 \text{ kg} \cdot \text{s}^{-1}$ at $T_{W,IN} = 80 \text{ °C}$ and $T_{W,OUT} = 50 \text{ °C}$ may fulfill both the temperature requirements and the process heating load.

In order to improve the feasibility of the SAHP system, only commercially available components are chosen. The characteristics of the main components of the system studied are collected in Tab. 1.

Component Parameter and value		
Compressor	Variable speed reciprocating compressor, swept volume 30.75 m ³ ·s ⁻¹ , rotational frequency 30 Hz – 70 Hz	
Gas cooler	329 mm x 119 mm, 138 plates, heat transfer area 5.58 m^2	
Evaporator	329 mm x 119 mm, 92 plates, heat transfer area 3.68 m^2	
Internal HX	329 mm x 119 mm, 72 plates, heat transfer area 2.88 m^2	

Tab. 1: Main characteristics of the components of the SAHP system

PV/T	Area 1.63 m ² , $\eta_{OPT} = 0.528$, $k_{1,PVT} = 13.658$ W·m ⁻² ·K ⁻¹ , $\eta_{EL,REF} = 0.1366$, $\gamma_{PVT} = 0.42$ %·K ⁻¹ , $T_{CELL,REF} = 56$ °C # of PV/Ts: 100, 200, 300, 800, 900, 1000
ETC	Area 3.018 m ² , $\eta_{OPT} = 0.835$, $k_{1,ETC} = 1.56$ W·m ⁻² ·K ⁻¹ , $k_{2,ETC} = 0.0017$ W·m ⁻² ·K ⁻² # of ETCs: 100, 200, 300, 800, 900, 1000
Heat storage	21 m ³ , 43 m ³ , 64 m ³ , 86 m ³ , 172 m ³ (equivalent to 6 h, 12 h, 18 h, 24 h and 48 h of operation)
Auxiliary boiler	Gas fired, $\eta_{TH} = 0.95$

Three different operating mode of the SAHP are considered:

• Operating mode 1: the low temperature heat produced by the PV/Ts is used as cold heat source in the heat pump evaporator. The high temperature heat produced by the heat pump and by ETCs is used in the pasteurization process.

• Operating mode 2: the mid temperature heat produced by the ETCs is used as cold heat source in the heat pump evaporator. The high temperature heat produced by the heat pump is used in the pasteurization process. PV/Ts do not provide any heat.

• Operating mode 3: the high temperature heat produced by ETCs is used in the pasteurization process. Neither the heat pump nor PV/Ts provide any heat.

It is worth specifying that in all the operating modes, any heat excess is stored in the heat storage or, conversely, the auxiliary boiler supplies the heat shortage. Regarding the power production, the PV/Ts produce power also in Operating mode 2 and 3. The power is used to drive the SAHP system (compressor and pumps) and the excess power is assumed to be completely used by the industrial process.

4. Results

The analysis of the SAHP is carried out for the city of Milan and for one year of operation. Two steps are considered in the analysis. In the first step several simulations are run to assess the influence of the number of PV/Ts, of the number of ETCs and of the heat storage size. In the second step an optimization process is carried out to identify the best system configuration both from the energetic point of view and from the economic point of view.

Fig. 3 shows the influence of yearly electrical energy surplus (left) and thermal energy supplied by the auxiliary boiler (right) as a function of the number of PV/Ts (x-axis) and ETCs (y-axis) for a storage volume equal to 86 m³. Starting from the electrical energy, a strong influence of the number of PV/Ts and a weak influence of the number of ETCs are found. Indeed, for any size of the ETC field, the electrical energy surplus increases significantly as the number of PV/Ts increases whereas, for any size of the PV/T field, the electrical it is almost constant if the number of ETCs is higher than a threshold value, approximately 100-140. Below this value, an increase in the heat pump operating time arises which, in turn, lead to an increase in electricity consumption and, therefore, a reduction in the electrical energy surplus. Considering the thermal energy supplied by the auxiliary boiler, the opposite trend is found since a strong influence of the number of ETCs and a weak influence of the number of PV/Ts arise. Quite obviously, for any PV/T field size, the amount of heat the auxiliary boiler has to provide reduces as the number of ETCs increases whereas, for any size of the ETC field, this parameter is almost constant as a function of the number of PV/Ts. The only exception to this analysis is the bottom-left corner where the number of PV/Ts and ETCs is too low to drive the heat pump, resulting in a large use of the auxiliary boiler

to supply heat.



Fig. 3: Yearly electrical energy surplus (left) and thermal energy supplied by the auxiliary boiler (right) as a function of the number of PV/Ts (x-axis) and ETCs (y-axis) for a storage volume equal to 86 m³.

The share of the heat production as a function of storage size (x-axis) and for some selected sizes of PV/T and ETC field (labels inside each bar) is reported in Fig. 4. First, a clear influence of the heat storage size may be found. Indeed, whatever is the number of PV/Ts or ETCs, the higher is the heat storage size, the lower is the auxiliary boiler share (green bars). Considering the production of process heat through ECTs (purple bars in operating mode 3 and red bar in operating mode 1), it is found that, with the only exception of the smaller storage size case, this operating mode achieves the highest share and, additionally, larger ETCs field (2nd and 4th purple bar in each group) benefit from the heat storage size more than smaller fields (1st and 3rd purple bar). The contribution of the SAHP to the share is largely dominated by the PV/T driven operating mode (operating mode 1, blue bars) rather than the ETC driven operating mode (operating mode 2, dark yellow bars) with an overall share of the SAHP almost constant and around 15%.



Fig. 4: Share of the heat production as a function of storage size

Once a general analysis of the overall performance is made, an energetic and economic optimization of the SAHP system is carried out. In the economic analysis, the cost of the auxiliary boiler is not considered since this component has to be used in any SAHP system. It is worth specifying that the energetic optimization is carried out with the aim of minimizing the auxiliary boiler consumption, whereas the economic optimization maximizes the Net Present Value (NPV) of the SAHP system. The cost of the components of the SAHP system are taken from a market survey and are collected in Tab. 2.

Component	Cost
Heat pump	65270€
PV/T	1200 €·(kW) ⁻¹
ETC	850 €·m ⁻²
Heat storage	1500 €·m ⁻³

Tab. 2: Cost of the components of the SAHP system

The results of the energetic or the economic optimization are reported in Tab. 3 and Tab. 4 respectively. As a first general comment it is possible to state that both the energetic and the economic optimal configurations lead to a reduction of the auxiliary boiler consumption since in the "boiler-only" scenario it accounts for 1158 MWh. Additionally, comparing the two sets of optimal configurations, it is found that the number of PV/Ts is equal to the maximum allowed by the problem constraints whereas the number of ETCs is 70%-150% higher in the optimal energetic configuration. Quite obviously, due to the larger ETC field size, the optimal energetic configuration has lower heat pump consumption, in the range 90.8% to 93.6% and, more importantly, significantly lower auxiliary boiler consumption, spanning the interval 49.1% to 83.8%. Conversely, the optimal economic configurations show superior economic parameters since the NPV is 26.9%-52.3% higher than the corresponding parameter in the optimal energetic configurations and, consequently, the pay-back time is 22.6%-39.8% lower. It is anyway quite interesting to state that the best optimal energetic configuration is achieved when the heat storage size is equal to 172 m³, whereas in the best optimal economic configuration the storage size is equal to 21 m³ considering the IRR and the pay-back time.

Tab. 3: Optimal energetic configuration that minimizes the auxiliary boiler consumption

Storage size	21 m ³	43 m ³	64 m ³	86 m ³	172 m ³
Number of PV/Ts	1000	1000	1000	1000	1000
Number of ETCs	400	480	480	460	440
SAHP consumption	30.7 MWh	30.2 MWh	30.2 MWh	30.3 MWh	30.5 MWh
Auxiliary boiler consumption	455.1 MWh	245.2 MWh	181.1 MWh	158.9 MWh	129.2 MWh
NPV	673.2 k€	716.2 k€	756.7 k€	793.1 k€	739.6 k€
IRR	9.8%	9.4%	9.5%	9.7%	9.1%
PBT	12.8 y	13.4 y	13.2 y	12.8 y	13.7 y

Tab. 4: Optimal economic configuration that maximizes the NPV

Storage size	21 m ³	43 m ³	64 m ³	86 m ³	172 m ³
Number of PV/Ts	1000	1000	1000	1000	1000
Number of ETCs	160	220	240	240	260
SAHP consumption	33.8 MWh	32.8 MWh	32.7 MWh	32.7 MWh	32.6 MWh
Auxiliary boiler consumption	543.3 MWh	374.4 MWh	320.8 MWh	311.8 MWh	263.1 MWh
NPV	1025 k€	1083 k€	1071 k€	1050 k€	939 k€
IRR	15.7%	14.4%	13.6%	13.2%	11.4%
РВТ	7.7 у	8.3 y	8.8 y	9.1 y	10.6 y

5. Conclusions

In the present study an energetic and economic analysis of a solar assisted heat pump system for pasteurization process is carried out.

First, the influence of the number of PV/Ts, the number of ETCs and the storage size on the system performance is analyze finding that the PV/T field size has a significant influence on the electric energy surplus and a negligible influence on the auxiliary boiler energy consumption, whereas the opposite occurs considering the size of the ETC field. Additionally, larger heat storages allow to better exploit the solar radiation since they tend to reduce the auxiliary boiler energy consumption.

Then, the optimal system configuration from the energetic or the economic point of view is identified finding that both systems lead to a reduction of the auxiliary boiler consumption. Additionally, the optimal energetic configurations exhibit larger size of the ETC fields and lower heat pump and auxiliary boiler energy consumptions whereas the optimal economic configurations have superior NPV and IRR and lower pay-back time.

6. List of symbols

$a_1 \dots a_{10}$	Manufacturer's coefficients in eq. 1
Α	Area, m ²
$b_1 \dots b_{10}$	Manufacturer's coefficients in eq. 2
$c_1 \dots c_3$	Pressure drop coefficients in eq. 13
C _P	Isobaric heat capacity, J·kg ⁻¹ ·K ⁻¹
G	Solar irradiance, W·m ⁻²
h	Enthalpy, J·kg ⁻¹
h _C	Convective heat transfer coefficient $W{\cdot}m^{\cdot2}{\cdot}K^{\cdot1}$
k	Thermal conductivity, W·m ⁻¹ ·K ⁻¹
k _{1,ETC}	Manufacturer's coefficient in eq. 12, $m^2 \cdot K \cdot W^{\text{-}1}$
$k_{2,ETC}$	Manufacturer's coefficient in eq. 12, $m^{2}{\cdot}K^{2}{\cdot}W^{{\cdot}1}$
k _{1,PVT}	Manufacturer's coefficient in eq. 11, $m^2 \cdot K \cdot W^{\text{-}1}$
'n	Mass flow rate, kg·s ⁻¹
NTU	Number of transfer unit, dimensionless
p _{0,GC}	Refrigerant pressure at gas cooler outlet, kPa
Q	Heat transfer rate, W
<i>R</i> *	Heat capacity rates ratio, dimensionless
t	Thickness, m
T_E	Evaporating temperature, K
U	Overall heat transfer coefficient, $W{\cdot}K^{\text{-}1}$
\dot{v}	Volumetric flow rate, m ³ ·s ⁻¹
Ŵ	Power, W

Greek symbols

ent in	eq.	10
	nt in	nt in eq.

Δp	Pressure drop, Pa
Е	Effectiveness, dimensionless
η	Efficiency, dimensionless

Subscripts

Α	Air
С	Cold stream
DIS	Compressor discharge
EL	Electrical
Н	Hot stream
IN	Inlet
MAX	Maximum
OPT	Optical
OUT	Outlet
PUMP	Pump
REF	Reference condition
SUC	Compressor suction
ТН	Thermal
W	Wall or water

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Solar Energy Opportunity Map for the Spanish Microbrewery Industry

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Abstract

Microbreweries are less energy-efficient and pay higher energy price than larger breweries. In addition, although in Spain the electricity price is up to 5 times higher than the natural gas, full-electric microbreweries have been identified. The integration of solar thermal systems is seldomly economically attractive since the production profile is commonly performed by batches during non-consecutive days. In this study, the Levelized Cost of Heat and Cold is calculated for a microbrewery located in the south of Spain, as a reference case. To achieve this, the heat and cold demand, the electricity consumption, and the price of the components and electricity are considered. Employing TRNSYS the heat and cold is calculated. Furthermore, it is proposed to install a PV system of 10 kW_p to reduce the LCOHC. The results are then obtained for the 52 Capitals of the Provinces of Spain. For the reference case the LCOHC varies between 0.28 and 0.323 €/kWh. When the PV system is considered in the calculation, the LCOHC is reduced to the range of 0.249 - 0.305 €/kWh. Moreover, the Discounted Payback Period is between 9.8 and 19.5 years. Additionally, a production profile that quintuples the actual beer production is proposed with a larger PV system. In this case the LCOH can be reduced to the range of 0.17 to 0.21 €/kWh. Therefore, the main contribution of this study is to show that regardless the location in Spain, the integration of a PV system in a fullelectric microbrewery would always present economic benefits compared to the base case without self-generation.

Keywords: LCOHC, photovoltaic, industrial heat and cold, TRNSYS.

1. Introduction

In December 2019, the European Commission announced the European Green Deal project, aiming to make the European Union climate-neutral by 2050. Moreover, the industrial sector has a leading role to play in the transformation towards a carbon-neutral economy. Currently, it accounts for 20% of the EU's of greenhouse gas emission (European Commission, 2019). According to the energy consumption of a company, it can be classified as energy-intensive or non-energy intensive. Therefore, this designation works as a starting point to identify energy efficiency potential of a company. Although the EU designates the food and beverage manufacturing as non-energy intensive, it is classified as an energy-intensive industry by U.S. Energy Information Administration (U.S. EIA, 2019). Besides, producing beer is a highly energy-intensive process accounting for up to 8% - 9% of total production costs (Sturm *et al.*, 2013; Kubule *et al.*, 2016).

Numerous studies of solar energy for the brewing are focused on medium and large size breweries. (Schmitt et al., 2012; Lauterbach et al., 2014,Eiholzer et al., 2017). Small and medium sized enterprises (SMEs) are diverse and commonly require actions targeting specific needs. The case of small and microbreweries is an example of this. Regarding energy consumption, three main characteristics are worth to mention:

- Small breweries cannot purchase large centralized efficient boilers and chillers that run continuously.
- Heat recovery strategies are challenging to apply, as the beer production is a batch process often performed on different days. Hence, additional costs for energy storage are involved.
- Since they are small energy consumers, their energy contracts are usually as regulated users, increasing the energy price compared with larger industries that negotiate more competitive prices.

Additionally, the number of microbreweries has steadily raised globally in the past two decades and the trend is that the market will continue to expand (Garavaglia and Swinnen, 2017). For instance, in Europe the number of microbreweries increased from 3,020 in 2011 to 8,203 in 2019. Particularly in Spain, a traditionally wine producing country, the number of registered microbreweries has increased from 70 in 2011 to 379 in 2019 (The

Brewers of Europe, 2021). When all Spanish microbreweries are counted, not only those in the official national registry, but the number of microbreweries also reaches 998 (for 2018).

The brewing process requires heat, cold and mechanical power. Commonly, heat is provided with fossil fuel, e.g. natural gas, whilst the latter two with electricity. However, certain microbreweries are operating completely on electricity since it is easier to comply with industrial safety regulation.

A previous feasibility study in Chile was performed by the authors based on a microbrewery that employs liquefied petroleum gas (LPG) for heat and electricity to supply cold by employing a compression chiller. One conclusion was that for a solar thermal system the discounted payback period can as low as 3.83 years, saving 40% of the annual thermal energy demand. Moreover, for a PV system that covers 82% of the annual electricity consumption, a DPP of 5.2 years can be achieved in provinces with high solar irradiation and high electricity price from the grid (Pino et al., 2020). On the other hand, a microbrewery located in Seville (Spain) can reduce its natural gas consumption and the corresponding CO_2 emissions by integrating a solar thermal system (flat-plate collectors). Nevertheless, the DPP is over 29 years due to the low natural gas price in Spain (Pino et al., 2019).

Furthermore, one of the few energy-related studies for microbreweries is based on a case study in South Africa. It presents an optimal solution, obtained by simulation results, to reduce the energy cost by implementing a grid-connected tracking PV system and a battery storage to the microbrewery (subjected to demand response). A payback period for the complete PV system of 13.8 years is reached.

In Spain both electricity and natural gas prices are regulated for small consumers. Since electricity price is between 0.126 and 0.199 ϵ /kWh (3.0A tariff), whilst natural gas is 0.0414 ϵ /kWh (TUR 2 tariff), both including specific taxes and distribution fees but not VAT, full-electric breweries have higher saving potential by including solar energy. Among the 100 breweries with larger PV systems reported globally in 2019, 74 are located in the U.S., 11 in Australia, and only 7 in Europe (van der Linden and Wolf, 2019).

This study presents an opportunity map for photovoltaic solar energy integration in Spanish microbreweries based on the Levelized Cost of Heat and Cold (LCOHC). The load profile is based on an actual Spanish microbrewery. Through simulations performed in TRNSYS the annual heat and cold demand are estimated for different location (Klein *et al.*, 2011). In addition, the investment cost and electricity tariff allow to calculate the LCOHC. Therefore, the main contribution of this study is to present economic feasible alternatives to conventional energy use in microbreweries, which commonly are not considered in the potential for solar energy analyses due to their small size and their challenging batch process.

2. Methodology

In order to calculate the Levelized Cost of Heat and Cold (LCOHC) it is vital to know the heat and cold demand. In addition, to calculate the demand for different location a simulation model that considers the local ambient conditions must be created. For that purpose, the methodology employed in this study is:

- Definition of the load profile and temperatures of the process.
- Adjustment of empirical models for the components that supply heat and cold.
- Simulation in TRNSYS of the components that represent the brewery's energy load and calculation of heat and cold demand, and electricity consumption.
- Calculation of the LCOHC for the different scenarios proposed, varying PV installed capacity and location.
- Creation of maps employing Geographical Information System (GIS).

2.1. Load profile:

Since the brewing process is performed in batches, especially in micro and small breweries, there is no common load profile that represents them all. In addition, the energy consumption is frequently required for short periods of time, causing high peaks of energy demand. To reduce this impact, thermal storages (hot and cold) are usually installed. Moreover, microbreweries commonly lack a centralized monitoring and control system. Therefore, to define the load profile for this study, a description of the process by the master brewer helped in establishing the

temperatures and duration of the different stages. In addition, the electric bills were reviewed.

There are three main components to supply the heat and cold demands:

- HVAC system for heating and cooling of the conditioning room. It is an air-air reversible air conditioner and heat pump. It works under an on-off scheme. The set temperature is 20°C.
- Water chiller to provide water (15% glycol) at -2 °C, which is stored in a 1.2 m³ cold storage tank.
- Electric heat resistors. There are 2 heat resistors of 10 kW that supplies heat to two kettles.

Non-invasive sensors were installed to obtain detailed data of the energy consumption and the temperature that define the process for 8 months, covering both winter and summer months. The temperature sensors were placed inside the conditioning room and at the water and air inlets and outlets of the chiller. In addition, energy monitoring clamps were installed in the HVAC system for a short period (2 weeks), then they were installed at the chiller and at the central board that control the heat resistors.

2.2. Modeling the components:

First, to model the HVAC system performance, the heat and cold demand of the conditioning room were estimated. The conditioning room is inside the brewery's facilities, specifically in a warehouse which indoor temperature is not controlled. The warehouse partially absorbs the impact of the environment condition over the conditioning room, i.e. solar irradiation and ambient temperature. Therefore, the thermal losses of the conditioning room were calculated in steady state at each time step. In addition, the interior temperature of the warehouse was estimated by a sinusoidal equation (eq. 1) that varies throughout the year and between day and night.

$$T_{indoor} = T_{avg} + (T_{max} - T_{min}) \cdot \sin\left(\frac{t}{8760} \cdot 360 - 100\right) + \sin\left(\frac{t}{24} \cdot 360 - 180\right)$$
(eq. 1)

Where T_{indoor} is the dry-bulb temperature of the interior of the warehouse and T_{avg} , T_{max} and T_{min} are the annual mean, maximum and minimum dry-bulb temperatures of the location, respectively.

The U-value for the walls of the conditioning room is 1 W/m²K and for the floor it is 2 1 W/m²K. There are also infiltrations of 1/h and 4 hours per day it increases to 2/h, considering activities performed in the conditioning room.

The set point conditions of the conditioning room are 20 °C and 50% RH. And it is assumed that the HVAC system is capable to maintain it, therefore the heat and cold demand are calculated. Consequently, the electricity consumption is calculated employing the COP (winter) and EER (summer). These performance parameters are calculated for each time interval employing the empiric model developed by Cherem-Pereira and Mendes (2012) to estimate a correction factor Z (eq. 2). The nominal nameplate values of the equipment are: Heating capacity of 3.5 kW, COP_{nominal} =3, and cooling capacity of 3.2 kW, and EER_{nominal} =2.8.

Correction factor
$$Z = \frac{Z_{real condition}}{Z_{nominal condition}}$$
 (eq. 2)

The correlation coefficients employed are the one presented by Meissner et al. (2014):

$$Z_{EER} = 1.3884740 + 0.076999 \cdot T_{wb,i} - 0.00093 \cdot T_{wb,i}^{2} - 0.05425 \cdot T_{db,o} + 0.0002746 \cdot T_{db,o}^{2} + 0.0001448 \cdot T_{wb,i} \cdot T_{db,o}$$
(eq. 3)

 $Z_{COP} = 1.3884740 + 0.076999 \cdot T_{wb,o} - 0.00093 \cdot T_{wb,o}^{2} - 0.05425 \cdot T_{db,i} + 0.0002746 \cdot T_{db,i}^{2} + 0.0001448 \cdot T_{wb,o} \cdot T_{db,i}$ (eq. 4)

Where, $T_{wb,i}$, $T_{wb,o}$, $T_{db,i}$, $T_{db,o}$ are the wet bulb and dry bulb temperatures of the inside of the conditioning room (where the evaporator is) and the outdoor (where the condenser is) in °C, respectively.

To model the air-water chiller performance, the simplified Gordon-NG model is employed. It is recommended by the ASHRAE, due to its simplicity of resolution to estimate the coefficients. It allows to calculate the inverse value of the COP (eq. 5). (Lee et al., 2012).

$$\frac{1}{coP} = -1 + \frac{T_{ci}}{T_{wo}} + \frac{1}{\dot{q}_e} \left(-\beta_1 + \beta_2 T_{ci} - \beta_3 \frac{T_{ci}}{T_{wo}} \right)$$
(eq. 5)
This model has been chosen based on the information available from measurements, its ease of use and its adequate adjustment for machines that work with a fixed speed compressor.

In order to obtain the regression coefficients (β s) a dataset of 3654 observations was used. Each observation corresponds to measurement in a 1-minute interval. The R value of the regression exceeds 0.999. The regression coefficients obtained are: $\beta_1 = 0.03055$, $\beta_2 = 11.54$, and $\beta_3 = 698.98$. Therefore, the regression model presented in eq. 6.

$$\frac{1}{cop} = -1 + \frac{T_{ci}}{T_{wo}} + \frac{1}{Q_e} \left(-0.03055 + 11.54 T_{ci} - 698.98 \frac{T_{ci}}{T_{wo}} \right)$$
(eq. 6)

Where, T_{wi} is the cold-water inlet temperature, T_{wo} is the cold-water outlet temperature, both in Kelvin, and heat \dot{Q}_e is the heat removed from the water stream in kW.

Finally, for the heat resistors a COP = 1 is employed. Hence, all the heat supplied is equivalent to the electricity consumption.

2.3. Simulation model

A simulation model developed in TRNSYS 17 is utilized to calculate the total annual thermal demand. The meteorological information is obtained from Meteonorm in TMY format (Meteotest, 2018).

The heating and cooling loads for the conditioning room are calculated according with the thermal losses to the environment and infiltration mentioned above.

In order to calculate the heating load, an input file with hourly values of water volume employed for the different set temperatures is provided. For instance, the process demands water at 70 °C, 95 °C, and 100 °C during the boiling process. For the latter, there is also considered heat for evaporation (10% of the fluid mass). The sensible heat to reach the set temperatures considers the initial temperature of the water from the mains (location dependent), except for the boiling process where it starts at 70 °C.

The cooling load that the water chilled needs to supply is composed by 5 variables. Two variables are part of the process (a) when the hot wort is cooled from 100 °C to 20 °C (to start the fermentation) and (b) when it is cooled again to 2 °C (for maturation). These values are read from the input file as volume of fluid that needs to be cooled. In addition, the thermal losses to the environment (at T_{indoor} of the warehouse) are considered: (c) for the fermenters in fermentation stage, (d) for the fermenters in maturation stage, and (e) for the cold thermal storage. The U-value for the fermenters is 0.35 W/m²K and for the cold storage 0.28 W/m²K.

When all the heat and cold demands are calculated for one time-step, the electricity demand is also calculated employing the instant performance indicators for the different components (COPs and EER). The time-step of the simulation is 15 minutes.

Finally, in the same TRNSYS model the PV system is modelled. The PV generation is calculated employing Type 94a (rated efficiency = 16.3%, Vmp = 37.4 Vdc, Imp = 8.6 Adc), whereas the inverter is modeled utilizing the Sandia Performance Model for grid-connected PV Inverters (King *et al.*, 2007).

For each time-step, the electricity demand and the PV generation are compared to calculate if electricity is obtained from or injected into the grid. In addition, the values are separated in three periods for each day in order to represent the time-of-use (ToU) tariffs that regulate small and medium enterprises subject to the tariff 3.0A in Spain.

2.4. Levelized Cost of Heat and Cold (LCOHC) and Discounted Payback Period (DPP):

The Levelized Cost of Energy is a well-established metric to compare specific cost per unit of energy during the entire lifespan of the project. It gained recognition in the power generation industry as it was employed to compare different technologies, e.g. a coal power plant versus wind power.

When considering solar integration in an industrial process (or for residential use), it is not so clear to define what the initial investment, O&M cost, and supplied energy should be. Therefore, a system boundary should be established. For instance, it is important to define if the LCOE will consider only the solar part or also the auxiliary

or existing components, a problem that power stations do not have since they are entirely built to supply electricity.

Within the results of IEA SHC Task 54 a guideline to calculate the Levelized Cost of Heat for solar thermal systems was published (Louvet *et al.*, 2017). The authors propose two levels for performing the calculation. The first one only considers the investment, O&M costs, and energy supplied by the solar system. The second one considers all the equipment employed to supply heat. Thus, the energy supplied is the total load. Consequently, the investment of the conventional system, e.g. a gas boiler, its O&M cost are also included in the analysis together with the solar system itself. The eq. 7 presents the formula to calculate the LCOH defined in the Task 54, where I₀ and S₀ are investment and subsidies, T is the period of analysis, C_t are the O&M costs for the period *t*, TR is the corporate tax rate, Dep_t is the depreciation for the period *t*, RV is the residual value after the period of analysis, *r* is the discount rate, and E_t is the heat supplied during the period which usually is an annual figure.

$$LCOH = \frac{I_0 - S_0 + \sum_{t=1}^{T} \frac{C_t \cdot (1 - TR) - DEP_t \cdot TR}{(1 + t)t} - \frac{RV}{(1 + t)T}}{\sum_{t=1}^{T} \frac{E_t}{(1 + t)t}}$$
(eq. 7)

To calculate the LCOHC (including cold) the LCOH definition was used, however neglecting some terms regarding corporate accounting (like depreciation, RV and TR) since commonly microbreweries finances are similar to residential or SME instead of large corporations. In addition, as in Spain there are no current subsidies at a national level, they are not considered (some Autonomous Communities have some subsidies available, however they are not permanent and certain conditions apply).

The formula employed to calculate the Levelized Cost of Heat and Cold (LCOHC) is presented in eq. 8. In this study, a period of analysis of 25 years and a 5% discount rate are utilized. No VAT is considered in the costs.

$$LCOHC = \frac{I_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}$$
(eq. 8)

On the other hand, the Discounted Payback Period (DPP) is the amount of time that it takes (in years) for the initial cost of a project to equal to the discounted value of expected cash flows. It is employed to estimate the profitability of a project, considering the time-value of money. If the resulting DPP is lower that the lifetime of the project it is profitable. The initial cash flow would be negative due to the investment, but the cash flows of the next periods (years) will be positive. Therefore, the DPP will occur when the negative cumulative discounted cash flows become positive. The DPP can be calculated as in eq. 9.

$$DPP = Year before DPP occurs + \frac{Cumulative Discounted Cash Flow in year before recovery}{Discounted Cash Flow in year after recovery}$$
(eq. 9)

2.5. Cost structure

For the LCOHC calculation there are two costs that should be included: the initial investment and the annual O&M cost. The initial investment values considered for this study are presented in Tab. 1 (including installation). These values were obtained from local quotations to suppliers (March 2021, in Andalusia, Spain). The price for the PV system is estimated as for a residential system due to its size from Jäger-Waldau (2019). Moreover, the expected lifetime and annual cost of maintenance as a percentage of the investment are also presented (VDI-Gesellschaft Bauen und Gebäudetechnik, 2012).

Component	Investment incl. installation, [€]	Lifetime, [years]	Maintenance as % of Io
Resistors – 2 x 10 kW	2500	5	0.0%
Chiller – 7.5 kW	5000	15	3.5%
Chilled water tank $$ - $1.2 \; m^3$	2160	15	1.5%
HVAC – 3.5 kW	1100	10	3.5%
PV (Jäger-Waldau, 2019)	1100 [€/kWp]	25	2.0%

Tab. 1. Investment and maintenance cost for the microbrewery's equipment.

The operational costs consider mainly the "fuel" employed to supply the heat and cold, in this case, electricity. In Spain, the regulated users observe a fix term and a variable term in their electricity receipt. The fixed term is composed of the contracted power that, if it is exceeded during the month, a penalization fee is charged. The

variable term depends on the energy consumed during the month. In addition, the tariff for SME (named 3.0A) considers 3 periods during the day: peak (P1), shoulder (P2), and valley (P3). Therefore, the contracted power cost is the sum of the three periods, and the energy costs are also divided according to the time if use. Tab. 2 present the values employed for this study, obtained from an actual electricity receipt of the studied microbrewery for March 2021. The fixed term is for the total year in euros per kilowatt. Additionally, there is a specific tax to electricity of 5.11% that affects the entire bill and VAT of 21%, which in this study is not considered for the LCOHC calculation. Moreover, a 3% electricity price annual increment is considered. Finally, since 2019 there is the opportunity for user with self-generation to inject the surplus generation to the grid and receive economic benefit for it, which is considered as a "negative cost" for this study. This compensation for selling electricity is expressed as a percentage of the purchased electricity price. This percentage is not fixed, instead each distribution company offers a regulated percentage for the user. The value presented in Tab. 2 is obtained from a formal quotation of March 2021. It is desirable that this percentage increases to encourage the distributed generation.

Tab. 2. Electricity price for a regulated user in Spain (Tariff 3.0A), employed in the study.

Electricity, ToU tariffs		
Contracted power: 25 kW		
P1 (peak)	42	€/(kW-yr)
P2 (shoulder)	26	€/(kW-yr)
P3 (valley)	18	€/(kW-yr)
Energy price P1	0.19	€/kWh
Energy price P2	0.17	€/kWh
Energy price P3	0.12	€/kWh
Specific Tax	5.11%	
VAT*	21%	
Estimated annual increment of price	3%	%/yr
Net-billing compensation ratio	23%	
No.4., WYAT is modify also dealed from the T	COUC	42

Note: *VAT is not included for the LCOHC calculation

Consequently, the O&M cost for the LCOHC calculation has the form of eq. 10. The replacement cost of equipment only applies if one of the components has reached its lifetime in the period t.

 $\begin{aligned} C_t &= Replacement \ Cost \ of \ equipment_t + Maintenance \ Cost_t + (1 + 0.03)^{t-1} \cdot 0.0511 \cdot \\ & [\text{Contracted power} \cdot (\text{P1} + \text{P2} + \text{P3}) + \sum_{i=1}^{3} ((enegy \ consumed_i - 0.23 \cdot enegy \ injected_i) \cdot \\ & energy \ price_i)] \end{aligned}$

In this study, the DPP is only calculated for the PV system. Hence, the annual cash flows correspond to the energy that is saved of being consumed from the grid and the earnings from the injected electricity to the grid.

Finally, when the energy demand is obtained from the simulation, the costs are calculated and the LCOHC and DPP are obtained. When this process is performed in several locations, the results are location-dependent and they can be included in maps created employing QGIS software (QGIS Development Team, 2021).

3. Results and Discussion

The first result obtained from the simulation correspond to the energy demand for the actual location of the microbrewery. Since the TMY data does not represent and actual year, it is not possible to compare the results with actual measurement. Nevertheless, the results were compared for two weeks of data, one in winter and one in summer, where there were production days and the ambient temperatures matches the ones of the measurements, obtaining satisfactory agreement.

In addition, the LCOHC of the reference case for all the locations was calculated. It means, the LCOHC of the current solution to supply heat and cold (no PV) for the current production profile, which is one batch per week (650 l), performed on Thursdays. It was calculated for the 52 different climates of the Provinces of Spain. The results are presented in Fig. 1. It can be observed that the range of the LCOHC varies from 28 - 32 cent€/kWh. Certain warmer and colder regions present the higher values due to the lower efficiency of the chiller and HVAC system with extreme temperatures. Moreover, the temperature of the water from the mains impacts the heat

demand. In addition, these values consider the electricity price depending on the time of the day where the energy is consumed, which happen to be more expensive during the working hours.



Fig. 1. LCOHC for the reference case not including PV in the different climates of the Capital of Provinces of Spain.

In order to select a size in PV system to be installed, a parametric analysis was performed for the actual location of the microbrewery (Jerez de la Frontera, Andalusia). The location has a latitude of 36°, Global Horizontal Irradiation (GHI) equal to 1903 kWh/m²-yr, and average dry-bulb ambient temperature $T_{a,avg} = 17.6$ °C. Fig. 2 present a contour diagram where x-axis represents the slope of the PV modules and the y-axis the installed capacity (from 1 to 30 kW_p). The color scale indicates in blue the lower values of LCOHC and the yellow color the higher. For the current location, it is observed that for a certain installed capacity, the lowest values are reached for a slope same as the latitude of the location (this is a climate with very hot summers). In addition, an optimum is not achieved. Hence, when the PV system is larger, lower values of LCOHC are achieved within the range of installed capacities analyzed. Nevertheless, there are other constraints that limit the total installed capacity:

- Roof available area. In this case it has not been considered.
- Distribution company limit: the maximum installed capacity should be lower than the contracted power, being 25 kW in this case.
- The payback period should be lower than the time of analysis, i.e., 25 years. In some regions with lower irradiation the PV system of 20 kW_p was nor recovered.

Consequently, for the analysis of all the Provinces of Spain a $10kW_p$ system with a slope same as the latitude is simulated.



Fig. 2: Contour diagram for the LCOHC parametric analysis regarding slope and installed capacity of the PV system for Jerez de la Frontera (left) and Burgos (right).

In addition, it can be observed in Fig. 3 (right) the heat demand for the heat resistors and the cold demand for the chiller depending on the mean ambient temperature. Both curves show a linear behavior when increasing the ambient temperature. However, the cold demand of the chiller is more dependent since the slope of the curve is higher than for the heat resistors (in absolute value).

When COP of the components and the PV generation are considered to calculate the electricity purchased from and injected into the grid, it can be observed in Fig. 4 that electricity from the grid tend to decrease with the ambient temperature. However, there is no clear trend in the scatter plot for the electricity injected into the grid (left). On the other hand, when it is compared with the annual GHI (right), a clear trend of the electricity injected into the grid is observed (increasing with the GHI), nevertheless, there is no clear trend for the electricity purchased from the grid depending on the GHI.



Fig. 3. Heat and cold demand supplied by the HVAC system depending on the annual mean ambient temperature of the 52 Provinces of Spain (left). Heat demand for the electric heaters (resistors) and cold demand of the water chiller depending on the annual mean ambient temperature of the 52 Provinces of Spain (right).



Fig. 4. Total electricity injected to the grid and bought from the grid when a 10 kWp PV system is installed, depending on the annual mean ambient temperature (left) and depending on the annual global horizontal irradiation (right) of the 52 Provinces of Spain.

Moreover, when the costs and cash flows are considered to calculate the LCOHC (Fig. 5), no clear trends are observed depending on the ambient temperature. For the scatter plot of LCOHC depending on the GHI, a slight negative slope can be noted, nevertheless, not completely clear. It can be inferred that higher PV generation (with higher GHI) reduces LCOHC, however, due to "hotter" climates the performance in cooling mode of the HVAC system and the chiller are reduced, hence more electricity for cooling is consumed.



Fig. 5. LCOHC when a 10 kWp PV system is installed, depending on the annual mean ambient temperature (left) and depending on the annual global horizontal irradiation (right) of the 52 Provinces of Spain.

The map of LCOHC for Spain considering a 10 kWp PV system is presented in Fig. 6. Furthermore, a map presenting the DPP of the same system is shown in Fig. 7. On the LCOHC map it can be observed that the values are in the range of 24.9 cent€/kWh in Sevilla to 30.5 cent€/kWh in Cantabria. The behavior is mostly even in the inner regions, with the higher values in the Mediterranean coast, the Gran Canaria Island, and in the north of the peninsula, where less solar irradiation is available. The case of La Palma de Gran Canaria is odd, since the nearby Tenerife island, with similar climate, has noticeably lower LCOHC. This might be related to the specific weather file considered for the location. Nonetheless, the main observation is that for all the locations the LCOHC with the PV system is lower than the reference system (Fig. 1).

On the other hand, when the DPP map is observed (Fig. 7) it can be inferred that regions with lower irradiation have a longer payback period (mainly in the north). The DPP ranges from 9.8 years in Seville to 19.8 years in Cantabria. Since this value is highly dependent on the cash flows, the period could be noticeable reduced if the net-billing ratio is increased (currently 23%), and therefore the earning from selling electricity to the grid increases.



Fig. 6. LCOHC for the different Provinces of Spain considering the actual production profile and a 10 kWp PV system installed at a slope same as the latitude of each location.

Although 10 years (best case for DPP) are less than half of the expected lifetime of the PV system, when discussed with the microbrewery owners it was a too-long payback period for taking a decision in this regard. Commonly, microbreweries are in a market expansion stage in the first years, therefore other investments have financial priority. Hence, subsidies and/or flexible financial mechanisms for clean energy integration could be offered to foster the solar integration in the industries.



Fig. 7. Discounted Payback of a 10 kWp PV system installed at a slope same as the latitude Period for the different Provinces of Spain considering the actual production profile.

Finally, a case where the beer production is increased by 5 times has been analyzed, brewing from Monday to Friday instead of only on Thursdays. In this case some modifications of the components were considered:

• The capacity of the chiller and the volume of the cold storage were increased 3 times. Since the cold demand for one batch is the same, it was not necessary to increase them by 5 times. Nevertheless, it was increased by 3 times because in this case the fermentation process and maturation process require 5 times more energy since there are 5 fermenters for each stage instead of 1 (calculated for the hotter weather: Sevilla). The investment (and replacement cost) was also increased by 3 times, which affects the maintenance cost too.

• The HVAC system capacity was increased by 3 times. Although the volume of the conditioning room was increased five-fold, the area of the walls does not increase in the same proportion, hence the thermal losses to the environment do not increase 5 times. Similarly, the investment on the HVAC system was considered 3 times higher than the reference case.

- The PV system installed capacity in this case was increased up to 20 kWp.
- The heat resistors were maintained the same since they are capable to produce 650 l of beer per batch.



Fig. 8. LCOHC for an intensive production profile (5 times per week, Monday to Friday).

The results for this "intensive" production profile are presented in Fig. 8. It can be observed that the LCOHC is lower than the reference case and the regular production profile with 10 kW_p of PV. The range of the LCOCH is

between 17.2 cent€/kWh in Sevilla to 20.8 cent€/kWh in Cantabria. These results are mainly due to a higher utilization of the components (chiller, HVAC, and resistances); hence, they are better amortized. In addition, to self-consume a higher share of the PV generation leads to higher economic benefits due to saving energy than selling it to the grid. The DPP for this case is in the range of 5.9 years in Seville and in Santa Cruz de Tenerife and 15.4 years in La Coruña.

Regardless of the "intensive" production profile presenting the lowest LCOHC, it represents a fictitious scenario that should be used as a benchmark for reference only. The labor would be highly increased, therefore, from the operation point of view it would be better to increase the size of the kettles and fermenters than the number of batches.

4. Conclusions

Although the brewing process requires heat at low temperature (<120 °C), there are few projects where solar thermal systems are integrated in the process. Therefore, the integration of a photovoltaic system to supply the heat and cold demand on breweries can lead to economic benefits. In this regard, for full-electric microbreweries the installation and operation of the PV system is simpler than solar thermal and supplies energy for cold and mechanical power. For the brewery of the case of study under the Spanish electric tariffs and solar resource, the PV system presented better results, i.e. lower Levelized Cost of Heat and Cold, for all the locations analyzed.

For this type of industry, where there are long periods where the product should be maintained under certain temperature condition, the heat and cold requirements are highly dependent on ambient temperature. However, the LCOHC has not a direct correlation with the ambient temperature since there are other effects affecting that impact the LCOHC. For instance, both the heat and cold demands tend to compensate the overall energy demand for hot and cold climates, commonly the locations with hot climates also have high solar irradiation levels, and the time-of-use tariffs also alter the energy cost depending on the time of day where the energy is consumed.

In addition, it is recognized that the Levelized Cost of Energy is highly dependent on the assumptions. For the LCOHC there is a similar conclusion, especially for the initial investment, energy price and energy price projections. Therefore, this study included the investment of all the components that supply heat and cold to be as thorough as possible.

Although, the net-billing ratio (23%) and the annual electricity price increment (3%/yr) are conservative, the LCOHC is lower than the reference case for all the locations analyzed (10 kW_p PV system). The LCOHC range for the reference case is between 0.28 and 0.323 ϵ /kWh, whilst in the case including the PV system, it is between 0.249 and 0.305 ϵ /kWh). The Discounted Payback Period of the PV system itself ranges from 9.8 to 19.8 years.

Nevertheless, the scenario where the production is increased by 5 times the components are larger, hence representing a higher investment, lower LCOHC values are achieved due to better amortization of the investment. The values of LCOHC in the intensive production scenario with a 20 kW_p PV system installed ranges from 0.17 to 0.21/kWh, whereas the DPP ranges from 5.9 to 15.4 years.

This study contributes to create knowledge regarding energy-related analyses for microbreweries. Commonly in Spain, the microbreweries do not know their energy consumption and perceive renewable energy as an expensive technology. The present results aim to encourage brewers to evaluate non-conventional energy sources, taking advantage of the current low price of PV, high available solar irradiation, and high electric prices from the grid.

Finally, to increase the renewable energy penetration in small industries, subsidies and flexible loans should be offered. Although in the scenario with no subsidies the PV system presents economic benefits, the brewery owners recognize that the payback period is too long and there are other investments that they would prioritize.

The future work that succeeds this study should include other solar technologies, e.g. solar thermal with and without concentration and hybrid PV-T modules, and a different load profiles, since brewing once a week is economically challenging to high-investment solutions as solar.

5. Acknowledgments

Alan Pino acknowledges the financial support from ANID PFCHA/DOCTORADO BECAS CHILE/2017.

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Techno-economic analysis for solar thermal integration point in an industrial boiler network: case study from dairy sector

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Abstract

This paper presents techno-economic analysis of a parabolic trough collector (PTC) for various integration points in a boiler network. The complete system is simulated with solar collectors utilized in 3 different integration schemes: a) feed water heating, b) direct steam generation, and c) process integration. The effect of integration point on the solar fraction, levelized cost of heating (LCoH), and carbon mitigation potential is presented for a real case dairy unit in Dubai. The simulations are performed using TRNSYS and MATLAB. Results show that the least global LCoH for highest solar fraction is achieved for process level integration. A relatively higher carbon mitigation can be achieved in steam integration, at expense of higher LCoH. The excess energy from the solar field can be stored in thermal storage tanks and can be utilized when there is intermittency in solar radiation.

Keywords: Solar thermal, Parabolic trough collector, Levelized cost of heat, integration schemes

1. Introduction

All countries are trying to reduce their emissions to achieve the target of limiting the increase in atmospheric temperature to 1.5°C. The share of renewable energy sources in the energy mix is increasing to realize the commitment agreed in the Paris Climate summit. To be within the targeted limit in temperature rise, reducing the emission of Green House Gas (GHG) from industries, transportation, and residential sectors is required. The final energy consumption in the world can be divided into; 17% is consumed in the form of electricity, 32% is consumed for transportation, and 51% is consumed in the form of heat. Among the total energy consumption by global population, 32% of the energy is consumed in the industries and in that 74% energy is required for heating application (REN21 Secretariat, 2021).

Most industries are still relying on fossil fuels to meet their thermal demand, which leads to significant GHG emissions. Solar Heat for Industrial Processes (SHIP) is a good alternative. Some reasons for the reluctance of some industries to implement these technologies include: previously installed fossil fuel technologies, lack of financial incentives, low cost of conventional fuel and variability of renewable energy sources.

In the industries, 30% of the process requires temperature below 150°C and 22% of them require the medium temperature category, which is between 150°C to 400°C (Hogrefe, 2021). Concentrated Solar Power (CSP) technologies available in the market and can meet all these heat demands. Food processing, textile, dairy and tea are some of the industries that require temperature in the medium and low-temperature levels.

The dairy industry or a dairy processing plant requires heat energy for almost all the processes, and this heat requirement is met from the heat generated by combusting fossil fuels. The dairy industry has processes to increase the shelf life of milk called pasteurization, processes to create value-added products from milk and Cleaning in Place (CIP) for the equipment. All these processes require heat in the range of 50°C to 200°C (Sharma, 2016). As per the journal article (Anna Flysjö, 2013), a leading dairy company in Europe emits between 1.1 kg and 7.4 kg of carbon dioxide while producing value-added products like whey-based products, cheese, butter etc.

These CO2 emissions can be eliminated if the heat is generated from a renewable source such as solar power.

Parabolic Trough Collector (PTC), which concentrates solar radiation to a receiver tube kept at the focal point, can produce the heat required to meet the thermal demand in the dairy industry. These types of collectors track the sun from east to west, thus capturing the maximum radiation.

For creating awareness among the policymakers and the industrial owner about the potential of solar thermal (ST) in reducing GHG emission, providing energy security and minimizing the dependence on fossil fuel, this study was done for finding the effect of integration points on solar fraction, Levelized Cost of Heat (LCoH) and carbon mitigation potential of a solar thermal system.

A step-by-step approach is used to conduct this study. Initially, a detailed literature review as well as interviews with several engineers at the operation from dairy industries were done. We obtained the operation profile of the dairy processes, heat demand, and techno-economic details of the existing boilers in the dairy sector. The results are further used to find the best commercially available solar thermal technology suitable for a given temperature range. This is followed by an energy audit of an existing system to analyse the existing cost of heating, load profile, and boiler information. Later, the system simulations with solar thermal collectors are performed for various integration points in the industrial steam network. The simulations are performed using TRNSYS and MATLAB. The output from the model is used to calculate the LCoH, solar fraction and carbon mitigation. For simulations, three integration schemes are considered namely; direct steam integration, process integration and feed water heating.

2. Renewable energy for industrial process heating and fossil fuel price trend

Industries demand a significant amount of energy for process heating. Solar thermal technologies available in the market such as flat plate, Parabolic Trough Collector (PTC) and Linear Fresnel collectors can meet the heat demand according to the temperature level needed for the industries. A report published by IEA (Weiss & Spörk-Dur, 2019) in 2019 shows that 741 solar thermal systems were installed for industrial heating worldwide by 2018. The utilization of heat energy from solar is expected to increase by 2021-2022, major energy-consuming nations like China, the USA, and European Union will be the reason for the growth and will account for 70% of the contribution (Abdelilah, et al., 2020). Low maintenance and simple technology are pushing factors for are acceptance of solar thermal technology among the industries.

Considering the case of the dairy industry, the heat demand is going to increase in the coming years, and the dairy consumption will be 99 kg/person for a year in the near future as per the UN food and agricultural organization's prediction (Shine, et al., 2020). To meet this high demand, the production of dairy commodity must also increase, which can lead to more carbon emission if fossil fuels are used for process heating. A significant number of industries rely on natural gas and coal for generating thermal energy. Reports show that the era of cheap natural gas is going to end. So natural gas will be a transition fuel as natural gas price is going to elevate in the coming years. Figure 1 is a graph (Shiryaevskaya, et al., 2021) showing that the natural gas is increasing.



Figure 1: Graph showing a positive trend in the natural gas price

3. Different schemes for integrating solar thermal system in the steam network

In an industrial steam network, the heat carrier medium's temperature, pressure, and flow rate will be different at different points. In this study, the solar thermal system is integrated into three-points: (a) supply level, (b) process level and (c) feed fluid level. According to the integration points, the integration schemes are direct steam integration, process integration, and feed fluid preheating. Different integration schemes are explained below.

3.1. Direct steam integration

In this type of integration, a derivative from the boiler feedwater is fed to the solar collector field. When the water passes through the solar collector field, the feed fluid will be partially evaporated and the mixture of hot water, and steam will be then stored in a steam drum. When the steam attains the required pressure, it will be fed to the main steam line. The schematic diagram below shows the integration of the solar thermal system for direct steam integration (Muster, et al., 2015).



Figure 2: Schematic diagram showing direct steam integration

3.2. Process integration

For a process integration, the heat carrier from the solar collector field is passed through a heat exchanger, connected in series to the conventional heat exchanger in the steam network near the process. The heat exchanger supplied from the solar can either meet the whole thermal demand of the process or a partial demand of the process. Figure 3 shows the schematic diagram showing the serial connection of the two heat exchangers (Muster, et al., 2015).



Figure 3: Schematic diagram showing process integration

3.3. Feed fluid preheating

The boiler feed water from the degasification section will be fed to the solar collector, where it will be converted to pressurized hot water. Then the hot water at high pressure will be provided to the conventional boiler for generating steam. Figure 4 is the schematic diagram of integrating solar thermal system for feed fluid preheating (Muster, et al., 2015).



Figure 4: Schematic diagram of feed fluid preheating

4. Key performance indicators

4.1. Levelizes Cost of Heat (LCoH)

Levelized Cost of Heat (LCoH) is a parameter used to compare different systems that generate thermal energy. The LCoH of a system depends upon type of technology, whether condition of the location, and some economic parameters (Kumar, et al., 2020). LCoH is the ratio between the cost expenditure on the system to the energy delivered by the system, expressed in ϵ /MWh. The equation and various parameters needed to calculate LCoH are shown below (Kumar, et al., 2020).

$$LCoH = \frac{I_0 - S_0 + \sum_{t=1}^{T} \frac{C_t (1 - TR) - DEP_t * TR}{(1 + r)^t} - \frac{RV}{(1 + r)^T}}{\sum_{t=1}^{T} \frac{E_t}{(1 + r)^t}}$$
(eq. 1)

Where, I_0 is the cost of the heat generating system, S_0 is any incentives or financial support from any organization, C_t is the cost required for operation and maintenance of the system, TR is the corporate tax rate existing in a particular location where the plant is located, DEP_t shows the asset depreciation, RV is the residual value of the system, E_t is the energy consumed by the system to generate the required heat to meet the demand, r is the discount rate, and T is used to express the life time of the system (Shah, 2021).

The global LCoH is the weighted sum of LCoH of the conventional heat generating technology and LCoH of the solar thermal technology. This parameter is relevant for when the heat generated by a conventional system is assisted by solar thermal technology. The equation used to find the weighted sum is given below (Shah, 2021).

$$Global \ LCoH = \frac{(LCoH \ of \ conventional \ system * Energy \ from \ boiler) + (LCoH \ of \ ST * Energy \ from \ ST)}{Energy from \ the \ whole \ system}$$
(eq. 2)

4.2. Solar Fraction

Solar fraction is the ratio of energy supplied from the ST system to the energy supplied to the total thermal energy demand. The value of solar fraction varies between 0 to 1. The heat load at each level of the steam system would be different. In this study, solar fraction at a particular level is considered instead of considering the contribution from the solar thermal system to the whole thermal energy demand of the plant (Shah, 2021).

5. Case description

The study case is located in Dubai. The location has good solar irradiation, but also lower fuel cost compared to other countries. The boiler is oversized so that the plant can expand in the future. The operation is not continuous at the moment, and it occurs mainly during sunshine hours. The plant chosen uses diesel as the fuel for the boiler at a price of 0.45 C/L, and the location has solar irradiation of 1883 kWh/m2. The boiler of the plant produces steam at a temperature of 110° C with a maximum flow rate of 7 ton/h and operates at an efficiency of 96%. The Figure 5 shown below shows the load profile of the plant.



Figure 5: Thermal load profile of the plant over a week

The plant requires heat for cleaning purposes in the milk reception section, pasteurization, and cleaning (CIP). The plant needs heat at 95°C at a maximum flow rate of 430 kg/h and 750 kg/h for cleaning process in the milk reception section and for CIP. For pasteurization, heat at 78°C at a maximum flow rate of 3 ton/h is needed. The boiler uses the condensate return from the boiler as feedwater. After the process, a condensate of temperature between 60°C to 75°C is available, which is combined fed back to the boiler.

As the heat between the range of 50°C to 200°C is needed for dairy processing, the PTC Absolicon T160 is used for analysis. The selected concentrated solar thermal collector can produce hot water up to 160°C and steam up to 8 bar pressures. The optical efficiency of the selected ST collector is 76.6%.

6. Results

The calculation of the global LCoH with the solar assisted heating system, LCoH with the conventional boiler system and the LCoH with the solar thermal system were found using the equation (1). The initial cost of the boiler is not considered in the calculation of the LCoH of the conventional boiler as the plant already had an existing boiler. By considering the lifetime of the boiler as 25 years, corporate tax rate of 2% and discount rate 4%, the LCoH of the conventional boiler is found out to be 44 ϵ /MWh without considering carbon tax. If there is a carbon tax of 62 ϵ /ton (Whiteley, 2020), then the LCoH of the boiler can go up to 60 ϵ /MWh (Shah, 2021).

The carbon emitted from the diesel boiler is found from the amount of fuel consumed by the boiler and CO2 emitted for a liter of fuel. The combustion of 1 L of diesel emits 2.66 kg of CO2 (AutoSmart, 2014). In the first year, the conventional diesel boiler demands 2386 MWh of energy, and it emits 629 tons of CO2.

Simulation results showed variations in the LCoH, solar fraction and carbon mitigated for different integration schemes. All the simulations are done by considering that a pressurized hot water storage will be included, limiting the energy wastage from the solar thermal system to 20% of the total energy supply of the solar thermal system.

6.1. Direct steam integration

The solar thermal system needs to generate steam at 3 bar pressure for supply level steam integration. The condensate return of 60°C is fed back to boiler in the plant considered for study. In that case, the annual load of the boiler would be 2386 MWh. Figure 6 shows the variation in the LCoH of the ST system and the solar fraction for the particular load for various field sizes. Figure 7 shows the carbon mitigated for different solar fraction for direct steam integration. The reduction in carbon emission is calculated from the reduction in the fuel consumed when ST system is integrated with the existing conventional steam boiler.

The highest solar fraction that can achieved for steam integration was 66.9% at a global LCoH of 41 €/MWh. More solar integration shows a major increase in the LCoH with minor increase in solar fraction.



Figure 6: Variation in LCoH and Solar fraction for different solar field integrated for supply level steam integration



Figure 7: Carbon mitigated at different solar fraction for direct steam integration

6.2. Process integration

For a process integration, it is required to increase the heat carrier temperature to 90°C. In this level of the steam network as the heat carrier is hot water and Δt is 65°C, the energy demand is 1201 MWh for a year. Same as the previous case, a storage tank is introduced to limit the wastage of energy from solar thermal system to 20% of the total energy supply from solar thermal system. Figure 8 shows the variation in the LCoH and solar fraction for several solar field sizes integrated to the process level and Figure 9 shows the carbon mitigated at different solar fraction. A global LCoH of 36 \notin /MWh can be achieved at a solar fraction of 85% for a process level integration.



Figure 8: Variation in LCoH and solar fraction against solar field size for process level integration



Figure 9: Carbon emission mitigated for at different solar fraction for process level integration

6.3. Feed fluid preheating

Feed fluid preheating is the minimum load in the steam network. The condensate return from the process together with the make up water temperature is increased to 100°C and fed to the boiler. The energy demand at this point is 118 MWh. Figure 10 shows the variation in LCOH and solar fraction of ST system for feed fluid preheating. Figure 11 shows the carbon emission mitigated at various solar fraction at the preheating level.



Figure 10: Variation in LCoH and solar fraction for feed fluid preheating integration



Figure 11: Carbon emission mitigated for different solar fraction for ST integration at feed fluid preheating level

7. Conclusion

This study aims to investigate integration of thermal solar power in different points in an industrial process on various parameters such as LCoH, solar fraction and carbon mitigation of solar thermal system. A PTC developed by the Swedish company Absolicon Solar Collector AB, T160, was selected for analysis. A real case of a dairy industry was selected to present a realistic scenario for the the cost of heating, load profile, and boiler information. Later a system simulation is done to check the variation in LCoH, solar fraction and carbon mitigation potential of the solar thermal system on three different integration points.

It was found that maximum demand occurs in the supply level and maximum carbon mitigation can be achieved if the solar thermal system is integrated in the supply level. Feed water preheating has the least carbon mitigation potential as the heat demand at the feed water level is small compared to process level and supply level.

In this study solar fraction is considered as the energy that the ST system can deliver at a particular load. The optimal solar fraction is calculated at 67% for supply level steam integration and an optimal solar fraction of 85% can be achieved for process level integration for the studied case. The LCoH of the ST system will go high at higher values of solar fraction and the system would become less economical. Almost half of the energy demand of the feed fluid pre hating can be done with ST, but a larger system will require a thermal storage tank with an associated increase in cost.

8. Discussion

There are different motivations to consider Solar Heat for Industrial Processes (SHIP). Industries may have a decarbonizing target; some have the aim of reducing their fuel cost and some industries adopt alternate technology as they may be required by local legislations. Depending upon the intension of adopting ST system, the technology, size and integration points vary. An industry with the aim of decarbonizing the production process may select an integration scheme with least priority to the financials and higher priority to the carbon mitigation potential of the system. Higher degrees of solar fraction require greater energy storage capacity than the optimal economic solution. SHIP is a proven technology with economical incentives that requires a tailor-made solution to determine the optimal solution for each application.

9. Acknowledgment

I am out of words to thank my colleagues, professors and parents who supported and encouraged me to finish this work. First of all, I am thank full to the sales and marketing team of Absolicon Solar Collector AB, Sweden for providing me the resources and knowledge to finish this study. I am thankful to Juan de Santiago for encouraging and supporting me to finish this work. This work was conducted within the STandUP for Energy strategic research framework.

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I-04. Solar Refrigeration and Air Conditioning

Solar Cooling for the Sunbelt Regions

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Abstract

In 2016, air-conditioning accounted for nearly 20% of the total electricity demand in buildings worldwide and is growing faster than any other energy consumption in buildings. The main share of the projected growth in energy use for space cooling comes from emerging economies. Therefore, the IEA SHC Task 65 "Solar Cooling for the Sunbelt Regions", started in July 2020, is focusing on innovations for affordable, safe and reliable Solar Cooling systems for the Sunbelt regions. The innovation is the adaptation of existing concepts/technologies to the Sunbelt regions using solar energy, either solar thermal or solar PV. The importance of the topic is reflected in the high number of experts participating in IEA SHC Task 65, especially as 50% of the Task experts come from industry and SMEs. This paper introduces the Task 65 and its first results, highlights the ongoing research projects and aims to attract a larger audience to get part of the initiative.

Keywords: Solar thermal cooling, PV cooling, Sunbelt regions, IEA SHC Task 65, MI IC7

1. Introduction

Global energy demand is growing, although its growth rate is less than in the past. Nevertheless, by 2040 an increase of 30% is projected by OECD (2017). Nowadays air-conditioning accounts for nearly 20% of the total electricity demand in buildings worldwide and is growing faster than any other consumption in buildings (OECD/IEA 2018). The undisputed rationales for the increase are global economic and population growth and thus rising standards of living. Growth in the demand of cooling is especially driven by countries with high temperatures. Three emerging countries (India, China, Indonesia) contribute to more than half of the annual growth rates. Additionally, the efficiency of the air-conditioners varies considerably. The most common systems run at half of the available efficiency (OECD/IEA 2018). If measures are not taken to counteract this increase, the space cooling demand could triple by 2050.

Nowadays e.g. in India, 30% of total energy consumption in buildings is used for space cooling which reaches 60% of the summer peak load. This is already stretching the capacity of the Indian national electricity supply dramatically (Patwardhan et al. 2012). In other countries peak load through air conditioning reaches >70% in hot day (OECD/IEA 2018). With the increase in demand comes the increase in the cost of electricity and summer brownouts, which have been attributed to the large number of conventional air conditioning systems running on electricity. As the number of traditional vapor compression chillers grow so do greenhouse gas emissions, both from direct leakage of high GWP refrigerant, such as HFCs, and from indirect emissions related to fossil fuel derived electricity consumption. Solar air-conditioning is intuitively a good combination, because the demand for air-conditioning correlates quite well with the availability of the sun. The hotter and sunnier the day, the more air-conditioning is required. Interest in solar air-conditioning has grown steadily over the last years. The latest numbers of worldwide installations in 2019 showed nearly 2,000 systems (IEA SHC 2020). Solar air-conditioning can be achieved by either driving a vapor compression air-conditioner with electricity produced by solar photovoltaic cells or by driving a thermal chiller with solar thermal heat.

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2. Adaption of solar cooling technologies

The knowhow capitalised in OECD countries (Europe, US, Australia, etc.) on solar cooling technology (both thermal and PV) is already very great, but very few efforts have been made to adapt and transfer this knowhow to Sunbelt countries such as Africa, MENA, Asian countries, which are all dynamic emerging economies They are also part of the global increase in demand for air conditioning (AC), where solar cooling could play an important role, as these are all highly irradiated regions of the world.

Therefore, the present IEA SHC Task 65 is aiming to develop innovations for affordable, safe and reliable cooling systems for the sunbelt regions worldwide (sunny and hot climates, between the 20th and 40th degrees of latitude in the northern and southern hemisphere). It should cover the small to large size segment of cooling and air conditioning (between 2 kW and 5,000 kW). The implementation/adaptation of components and systems for the different boundary conditions is forced by cooperation with industry and with support of target countries like India and UAE through Mission Innovation (MI) "Innovation Community on Affordable Heating and Cooling of Buildings" (MI IC7 2021).

3. General objectives of IEA SHC Task 65

The key objective of this IEA SHC Task 65 is to adapt, verify and promote solar cooling as an affordable and reliable solution in the rising cooling demand across Sunbelt countries. The (existing) technologies need to be adapted to the specific boundaries and analysed and optimized in terms of investment and operating cost and their environmental impact (e.g. solar fraction) as well as compared and benchmarked on a unified level against reference technologies on a life cycle cost bases. Solar cooling should become a reliable part of the future cooling supply in Sunbelt regions. After completion of the IEA SHC Task 65 the following should be achieved:

- Increase the audience and attention on solar cooling solutions through the combination of MI IC7 and IEA SHC activities and the entire stakeholders.
- Provide a platform for the transfer and exchange of know-how and experiences from OECD countries, already having long experiences in solar cooling, towards Sunbelt countries (e.g. Africa, MENA, Asia, ...) and vice versa.
- Support the development of solar cooling technologies on component and system level adapted for the boundary conditions of Sunbelt (tropical, arid, etc.) that are affordable, safe and reliable in the medium to large scale (2 kW-5,000 kW) capacities
- Adapt existing technology, economic and financial analyses tools to assess and compare economic and financial viability of different cooling options with a life-cycle cost-benefit analyses (LCCBA) model.
- Apply the LCCBA framework to assess case studies and use cases from subtasks A and B to draw conclusions
 and recommendations for solar cooling technology and market development and policy design.
- Pre-assess 'bankability' of solar cooling investments with financial KPIs.
- Find boundary conditions (technical/economic) under which solar cooling is competitive against fossil driven systems and different renewable solutions.
- Establishing of a technical and economic data base to provide a standardized assessment of demo (or simulated) use-cases.
- Accelerate the market creation and development through communication and dissemination activities.

4. First results of the Subtasks

4.1 Subtask A - Adaptation

Different climates found in the Sunbelt Regions are characterised by particular boundary climatic conditions to be considered during the design process (e.g. temperature, humidity, presence of dust, availability of tap water, etc.). The selection and the actual effectiveness of all components and the performance of the solar cooling systems are strongly influenced by the combination of operating conditions such as solar irradiation, ambient temperature, relative humidity, wind, and other parameters. Once the conditions are documented through reliable data, the components and systems can be selected from a specific regional market or/and adequately adapted. In case that component/system cannot be operated under certain boundaries, the operation limits must be documented: a well-documented summary of available procedures, components and systems is a base for promoting solar cooling and demonstrate the current state of the art.

The following results have been achieved in Subtask A so far (October 2021).

A1: Climatic Conditions & Applications

In general, climatic conditions and typical applications for (solar) cooling are strongly depending on the location. Therefore, a geographic information system (GIS) has been used to process this data. GIS is a computer system for capturing, storing, checking, and displaying data related to positions on Earth's surface. Most relevant GIS data are already available from different sources, such as solar radiation data, climatic data, population data etc.

In activity A1, a GIS software is used to combine this data in such a way that local reference boundary conditions for solar cooling systems in the sunbelt regions can be determined. In the scope of this activity A1 these results are used to derive boundary conditions for solar cooling systems and its components. By analysing this data, information about locally applicable solar cooling systems will become available. This aims to understand the reference boundary conditions for adaptation of the components and solar cooling systems (link to Activities A2 and A3). By additional, using population density data, for example, gives a base for future market potential studies on certain products / technologies.

The first steps in Activity A1 has been the evaluation of how to combine and which dates to combine. In a first approach the following conditions and sources are considered:

- Geographic areas that are regarded to require cooling include latitudes between 40°N and 40°S.
- Solar direct normal irradiance (DNI).
- Population density/Built-up areas/Settlement levels.
- Climate zones (Köppen-Geiger climate classification system).

A2: Adapted components

A specific survey has been designed and spread among experts to better understand how to combine the existing components with the climatic boundary conditions and typical applications with the necessary adaptation from the technical point of view. The data are currently under the collection. The elaboration will take into account the involved countries and the Köppen climate classification (Figure 1). Such a climate classification divides climates into five main climate groups, with each group being divided based on seasonal precipitation and temperature patterns. This approach will provide an appropriate qualitative classification of systems and components consequently.



Fig. 1: Updated Köppen-Geiger climate map used for the classification of the data collected

4.2 Subtask B - Demonstration

Although solar cooling has a long history, first examples were built in the 1990s, a real market couldn't be established anywhere. Roughly 2,000 solar (thermal) cooling systems exist worldwide. Most of them can be declared as customized, early-stage systems. PV supported cooling developed in the recent years, whereas PV is often only attached to a common electrical driven system and real control and optimized support (or increase of self-consumption) is rather seldom.

Several technical and mostly economic reasons are still preventing solar cooling from a wider market uptake. Besides these barriers, the most important approach for introducing these technologies in the Sunbelt is a wide range of demonstrations. It must be assured that solar cooling is seen as a technical reliable, economic viable (reasonable), and smart solution. The future perspective in Sunbelt countries through the adaptation of components and systems need to be proven by monitored best practice examples for all kind of system configurations and applications.

A first step to enter the specific markets is to ensure know how transfer for current solar cooling system designs and monitoring guidelines. Raising greater awareness for the technology, its technical and economic potential among end users and operators is crucial for further dissemination. Lessons learned through previous programs (e.g. past four IEA SHC Tasks) will be recognized and shortcomings avoided. More challenging climatic conditions require adaptation of components and systems (Subtask A) that leads to new insights and additional lessons learned.

When introducing best practice demonstration sites, the quality of the delivered data must be beyond any doubt. The definition of necessary data quality in terms of resolution and accuracy needs to be provided clearly and checked for each of the solar cooling systems (and single component tests) provided by any participant. A four-eyes principle will be implemented to keep the quality on the self-imposed level.

Future wider implementation of solar cooling systems relies deeply on initial cost optimization. Currently, 40-60% of the life cycle costs can be allocated to these costs. Further important measures are reliable, durable components that reduce the replacement and maintenance costs. Solar cooling systems to date already reached very high efficiencies (e.g. electrical seasonal performance factors > 15, low water consumption for heat rejection, etc.). Correspondingly, the operational costs are low compared to the other costs (Neyer and Koell 2017).

However, that might be changing if challenging climatic boundaries in Sunbelt countries prevent highly efficient solutions. Clear decisions should already be drawn in Subtask A when adapting certain components or systems. Finally, one key towards affordable systems, is extensive standardization work on system (or parts of the systems e.g. collector field, heat rejection, pumps, etc.). Standardizing the design, the manufacturing process, the implementation and the commissioning phase can drastically reduce the initial costs and contribute to competitive

solutions.

When the quality of monitoring data is evident, there is a good base to initiate the improvement of the performance of the demonstration systems accordingly. The comparison of designed and monitored data will lead to lessons learned and to optimization measures. Finally, the economic criteria that will be elaborated together and shared with interested audiences through the dissemination activities.

Achievements for Subtask B to date (October 2021).

B1 & B2: Surveys conducted

Detailed questionnaires were designed and submitted to all Task 65 experts. The expert's feedback will provide an overview of established solar cooling systems and the various components in the Sunbelt Regions and will support the notion to derive integration guidelines for solar cooling projects.

• The implementation of solar cooling systems across the Sunbelt Regions is a key activity among this Task. The collection of system designs and evaluated monitoring data of existing and new demonstration plants is the basis for the calculation of technical and economic KPIs.

The comparison of calculated, designed, and practical field performance is used to evaluate and improve the performance of the solar cooling plants. Lessons learned can be derived out of the deviation of design and field performances as well as general design rules.

• The large diffusion of solar cooling technology in the market does not depend solely on the technical and economic aspects, but also on the systematic approach for the design and installation of systems in different climates. This will present manageable guidance for easy integration to professionals who are not experts on the specific technology.

Even though design guidelines are well documented in deliverables of previous tasks (Task 48, 53), the current activity leverages this knowledge to include new concepts, such as a) hybrid cooling systems (including solar thermal, solar Photovoltaic), b) systems for high solar cooling fraction, and c) standard modular packages for solar cooling solutions. This activity is dedicated to keep an eye on the technical research and developments as well as to produce an extensive report on "Good Practice" examples of existing solar driven cooling systems.

B3: Key Performance Indicators

Although the key performance indicator definition was already proceeded often, there is still no standard and during the entire solar cooling community often a mix of non-comparable KPIs is used to express the quality of systems. This is not only confusing for end-users / operators / policy makers but also misleading the discussion among the experts. Thus, first the collection of existing technical and economic KPIs among finalized and ongoing IEA SHC Task but also from other sources is in the focus.

Information collection on definition and update of KPIs for technical and economic point of view for different stakeholders, especially end consumers, operating companies, ESCOs, policy makers, etc. has started.

4.3 Subtask C - Assessment and Tools

The concurrent technical, economic and financial assessment of solar cooling options is of high importance in each stage of the life cycle of a project, starting with comparison of different technology options and pre-design, detailed planning, optimizing of operation but also for policy design with proven concepts. In all life cycle phases, it is crucial to have corresponding tools that deliver the necessary information and key performance indicators for the different stakeholder. The KPIs need to take into consideration economic, financial, social and environmental issues as well as other 'Multiple Benefits'. Tools and their specific outputs permit to provide guidance on optimized system design and implementation and show the level of quality of both the most critical components and systems.

Assessing solar cooling along the sunbelt countries is further challenging due to different local framework conditions such as energy prices, investment cost of components, energy conversion factors, conventional technical reference systems. A comprehensive database of these technical and economic parameters is crucial to deliver prompt and accurate KPIs. However, beside detailed local results a set of generalized KPIs should be provided under standardized technical and economic boundaries to allow comparison, general conclusions and trend analyse across different solar cooling concepts (e.g. PV vs. ST, SE vs DE, etc.)

A thorough technic-economic-financial analyses based on an LCC assessment allows to answer questions like: (i) Which technical solutions to implement (e.g. higher CAPEX investment in exchange for lower OPEX)? (ii) Influence on cash flows? (iii) Calculation of bids to clients (iv) Effects of equity and debt financing shares? (v) Needs for subsidies/grants? (vi) Which parameters to monitor? Target-performance comparison? (vii) project reporting and decision making (e.g. to management boards, project stakeholders) (viii) financial engineering for reporting, negotiations & due diligence with Financiers (FI) (ix) subsidy or funding demand calculations (amount and timing) for policy makers ... and many more.

Several tools, models and methods are available, which need to be screened, evaluated and adapted for solar cooling in sunbelt countries. A great number of these tools and methods are well known or even developed by previous IEA Task participants. However, taking the targeted countries and the number of new interested participants an iteration for reviewing should be set before getting into action of adaptation.

Finally, when all question can be answered satisfactorily with the corresponding tools and KPIs there is a need to show the future perspective of solar cooling. Thus, sensitivity analysis on most critical parameters are of great interest. It is to analyse the potential of future developments of conventional technology, energy prices and optimization potentials of components/systems of solar cooling. These parameters are e.g. investment costs (solar/ conventional), electricity price (energy/capacity), electrical efficiency (solar/conventional), etc.

The following results have been achieved in Subtask C so far (October 2021).

C1: Design tools and models

It is to review and adaptation of tools and models for technical and financial assessment and design for solar cooling and the different project's phases from pre-feasibility to simulation to monitoring. Different solutions are available and of interest among the interested participants (from mobile apps to dynamic simulation models for consultants, manufacturer, researcher, etc.), which need to be discussed and consolidated. Each of the tools and models can support the implementation of solar cooling in sunbelt countries, if it is used target oriented.

The focus in this activity is the documentation of the tools and their specific application, to provide measured data for validation of the tools and the adaptation of selected ones for subelt countries. The following sections described the methods applied to achieve the main aim. At the time of writing this report the research based on a literature review has been completed, and a set of questionnaires was developed and distributed among the participants.

C2: Database for technical and economic assessment

The elaboration of the database and collection of technical (e.g. standard reference systems, etc.) and economic data (energy prices for electricity, natural gas, etc.) for different components (Investment, maintenance, lifetime, etc.) and for the different sunbelt countries (based on subtask B demo cases) has been started and is the bases for the following assessments of the various solar cooling concepts.

The data base includes future scenarios for technical and economic boundaries (e.g. efficiency of conventional chillers, energy prices) to provide the base and a solid framework for the sensitivity analyses and future scenarios. The database elaboration is also including review of existing useful information of IEA knowledge (e.g. IEA SHC Task 54, and others).

C3: Assessment mechanism

This activity is working closely with B3 activity, the review of existing tools (other IEA SHC Task, ...) and methods for technical (SPF, PER, fsav, etc.) and economic (LCC/CAPEX/OPEX, LCOH/LCOE, LCCBA etc.) provides the bases to select the necessary KPIs for different project phases and stakeholders.

A selection of one tool/platform will be forced to be used by this Task, the adaption of methods and integration of the database (C2) are the core activities. Whereof the focus is to provide the corresponding methods for the analyses and creation of assessments for certain stakeholders.

4.4 Subtask D - Dissemination

A wide penetration of solar cooling in sunbelt countries is not only depending on the accomplishment of technical barriers. Non-technical barriers often have a critical role. Financing, policy advise, and dissemination/communication of success stories are among the important activities to overcome also non-technical barriers.

The intermediate and finale results need to be spread across the different stakeholders from end-users, industry, operators, policy makers, etc. across the sunbelt countries and the interested audience. The focus is on the implementation of target specific promotion activities based on the collected results, upgrade of material for dissemination for external communication, the implementation of knowledge transfer measures towards the technical stakeholders, the development of instruments and their provision for policy makers.

At the time of writing (October 2021), the following results have been achieved in subtask D.

D1: Task65 website established and scientific papers published

A website included into the IEA SHC portal has been created, see <u>https://task65.iea-shc.org/</u>. This website profits from the crosslinks among the participants of Task 65 and benefits from their popularity, resulting in increased page views. This website firstly presents the Task purpose and activities and secondly the Task results. It also lists all Task participants and observers.

In the future, the website will also host an online best practice collection webpage, presenting the system concepts, state of the art of cooling markets, the main lessons learned and the entire technical and economic KPIs. After the end of the Task the website will become an archive of the Task's collective work results.

Publications so far include:

- Jakob U. and Neyer D. (2020). "Solar Cooling for the Sunbelt Regions a new IEA SHC Task". Proc. of EuroSun Conference 2020
- Neyer D. and Jakob U. (2020). "Solar Cooling for the Sunbelt Regions a new IEA SHC Task". Proc. of 6th Yangzi River Delta International Conference on New Energy 2020

D5: Workshops conducted

- SHC Solar Academy Training for CCREE, Nov 10th 2020 (online)
- National Workshop for China, Dec 5th 2020 (online)
- National Workshop for Austria, March 24th 2021 (online)
- Industry Workshop Task 65 + HPT Annex 53, Mar 25th 2021 (online)

D3 & D6: Guidelines and stakeholder engagement

Work has been started on the compilation of new guidelines for solar cooling design with a focus on the specific constraints and opportunities in sunbelt countries. Further, a first round of identifying potential stakeholders in sunbelt countries has been completed, with a milestone achieved in time. The stakeholders shall then be encouraged and assisted in initiating first solar cooling projects in their respective countries.

5. Strong industrial involvement

The IEA SHC Task 65 aims to strengthen the relationships between stakeholders from research and industry and the public to raise awareness of the cooling markets in the Sunbelt countries for solar cooling in future strategies for energy and CO2 reduction in buildings and industrial processes. Therefore, the (existing) technologies need to be adapted to the specific boundary conditions, analyzed and optimized in terms of investment and operating cost and their environmental impact (e.g., solar fraction), and compared and benchmarked on a unified level against reference technologies on a life cycle cost basis.

The strong interest by industry and business is reflected in the number of SHC Task 65 participants from solar thermal collector manufacturers, sorption chiller manufacturers, system suppliers, consultancies, business developers, and ESCOs – overall, 50% of the 77 Task experts are from industry and SMEs.

6. Trends and outlook

One of the main trends in the upcoming years will be that more and more hybrid system solutions of all kinds in the field of solar cooling will come onto the market. They will offer high CO₂ savings also in small to medium cooling capacity ranges with good economic efficiency at the same time. Furthermore, in the area of medium-temperature systems (solar collector temperatures around 160-180 °C) and double-effect absorption chillers, there will be solutions with better efficiency and profitability, since they will have smaller solar fields and lower heat rejection capacities to achieve an investment advantage of up to 40% compared to conventional solar cooling systems.

However, Solar Cooling is still a small niche market with about 2,000 systems deployed globally as of 2020. Due to changing distribution channels and B2B sales of the sorption chillers, the tracking of newly installed solar driven systems is difficult and can only be estimated. Small units with capacity lower than 20 kW are getting more compact (and thus cheaper in upfront costs) and focused the mass markets. The sector of medium to large scale projects, 350 kW - 2,000 kW, is dominated by engineered systems. Still 70% of the small and medium capacity (<350 kW) solar cooling systems worldwide are installed in Europe.

Consequently, the focus on potential markets for solar cooling technologies is becoming more and more important to get out of a niche market. Therefore, the knowhow capitalized in OECD countries (Europe, US, Australia, etc.) on solar cooling, both thermal and PV, has to be adapted and transferred to Sunbelt countries such as Africa, MENA, Asian countries, which are all dynamic emerging economies. For this reason, new developments and innovations for affordable, safe and reliable cooling systems for the sunny and hot climates in the Sunbelt regions worldwide, like Brazil, have been started such as the IEA SHC Task 65 (Jakob et. al. 2020) cover the medium to large size segment of cooling and air conditioning between 2 kW and 5,000 kW.

7. Acknowledgments

This work has partially received funding from the German Federal Ministry for Economic Affairs and Energy (BMWi / PtJ) under grant agreement No. FKZ 03ETW024B (SorptionTakeOff).

The funding of Austrian's participation of IEA SHC Task 65 (FFG no. 883011) through the Austrian Research Promotion Agency (FFG), the program "research cooperation international energy agency" and the Federal Ministry on Climate Action, Environment, Energy, Mobility Innovation and technology is gratefully acknowledged.

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I-05. Solar Cooking and Food Processing

Development and Implementation of a Performance Evaluation Process (PEP) for Solar Thermal Cooking Devices

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Abstract

Solar Cookers International staff designed and built portable test stations for a performance evaluation process (PEP) for solar thermal cookers in response to a specific need expressed by the solar cooking sector that an independent, neutral agency develop a testing process for solar thermal cooking devices. The PEP test stations are based on commercially available components, including thermocouples, an anemometer, a pyranometer and Arduino hardware. The test station control software was designed to automate the American Society of Agricultural and Biological Engineers (ASAE) S580.1 protocol for Testing and Reporting Solar Cooker Performance; it measures temperature changes in an amount of water proportional to the intercept area of a solar cooker, while monitoring wind speed and solar insolation, for normalizing results. With its development and implementation of its PEP solar cooker testing program, Solar Cookers International has built the capacity for testing solar cookers according to internationally agreed upon standards. PEP measurements produce the standardized cooking power performance specifications of solar cookers, and those specifications can guide customers and investors in making informed decisions.

Keywords: Testing standards, Solar cookers, Sustainable development, Solar thermal cooking, Tier 4 cookstoves

1. Introduction

According to the World Health Organization, for the approximately three billion people cooking food by using biomass fuel such as firewood, charcoal or animal dung, smoke particulates from cooking indoors is linked to some 4.3 million premature deaths annually worldwide (World Health Organization, 2016). It also is having negative impacts on the health of people, mostly women and children, regularly exposed to high levels of indoor air pollution. Solar thermal cookstoves that convert solar energy directly into heat energy are viable options for clean sustainable cooking that are beneficial for all, including the most vulnerable populations.

Solar cooking devices harness free, solar energy with no-emissions, clean sustainable cooking. Solar cookers collect solar energy with reflectors, absorb solar energy with black surfaces to transform solar energy to heat energy, and retain heat using insulation. People can generally obtain a solar cooker by purchasing a commercial product, by building one using an open-source design, or by innovating and implementing a new design. Prices for commercial solar cookers range from tens to hundreds of US dollars.

Types of solar cookers include the reflective-panel, box oven, parabolic reflector, evacuated tubes, Fresnel lenses and Fresnel mirrors. Institutional solar cooking systems are another type of solar cooker. These systems can be mounted on rooftops to concentrate solar energy, heat water, and create steam, or heat a thermic fluid, such as oil, that is transferred to a kitchen inside the building. In India, for example, there are institutional solar cooking systems that power mega kitchens that can cook tens of thousands of meals per day (Eswara & Ramakrishnarao, 2013).

Solar cooking has numerous benefits that can transform lives, particularly for women and girls in developing regions who are disproportionately exposed and impacted by harmful aspects associated with acquiring and using combustible cooking fuels such as firewood and charcoal. Solar cookers are suitable for nutritious meals, like legumes and pulses that are otherwise fuel-intensive to cook. Furthermore, with solar cooking, less time is spent scavenging for firewood, freeing up time for education and micro-enterprises; indoor air quality improves; deforestation is reduced; and family budgets for cooking fuel can be reduced (Bigelow, Fox, & Hughes, 2020). Solar cookers can pasteurize water, killing water-borne microbes (bacteria and viruses)

(Ciochetti & Metcalf, 1984). Solar dryers heat their contents using solar thermal methods to dehydrate and preserve food, which adds post-harvest value and increases food security (Eswara & Ramakrishnarao, 2013).

Solar cooking can make a positive impact on all 17 United Nations Sustainable Development Goals (SDGs) (United Nations, 2022); hence, solar cooking's potential for social, economic, and environmental solutions suggests it for bold and transformative steps which are urgently needed to shift the world to a sustainable and resilient path for environmental and human preservation.

Solar Cookers International (SCI) is a non-profit organization whose mission is to improve human and environmental health by supporting the expansion of effective carbon-free solar cooking in world regions of greatest need. SCI leads through advocacy, research, and strengthening the capacity of the global solar cooking movement. SCI is a convener that connects 500+ collaborators in 135 countries and hosts the Solar Cooking Wiki that has over 1,700 pages of information about solar cooking, including open-source design plans (Solar Cookers International, 2022).

SCI is an independent and brand-agnostic international agency. Because of its objective leadership status and expertise, SCI was well-positioned to respond to the solar cooking sector's request for an independent organization to develop a platform for evaluating solar cookers according to existing testing standards. The outcome is SCI's development and implementation of the Performance Evaluation Process (PEP) for testing the thermal performance of solar cookers. PEP implementation is poised to boost the solar cooking sector and enhance the impact from use of solar cookers; building credibility and verification for the solar cooking sector; encouraging manufacturers to develop superior products; and guiding project managers in selecting appropriate solar cookers for their projects.

In developing the PEP, SCI has established a standard testing platform for measuring the thermal performance of no-emissions solar cookers. SCI is included on the list of Regional Testing and Knowledge Centers (RTKCs) posted by the Clean Cooking Alliance (Clean Cooking Alliance, 2022). In addition to SCI's testing locations in California, USA and New York, USA, SCI has provided instrumentation and training to two other RTKCs (Center for Rural Technology, Lalitpur, Nepal; and University of Nairobi, Nairobi, Kenya), which now have the capacity for PEP testing of solar cookers in their respective regions.

2. Theoretical framework

There are multiple ways to evaluate a solar cooker, such as these existing approaches for evaluating the thermal performance of solar cookers: 1) ASAE S580.1 Testing and Reporting Solar Cooker Performance (American Society of Agricultural and Biological Engineers, 2013); 2) the Indian Standard: Solar Cooker - Box Type - Specification (Bureau of Indian Standards, 2000); and 3) the Focusing Solar Cooker (Ministry of Agriculture of the People's Republic of China, 2003). After reviewing those approaches, SCI chose to base its testing platform on the ASAE S580.1 protocol. The ASAE S580.1 protocol was initiated in January 1997; has received further evaluation (Funk, 2000) (Ebersviller & Jetter, 2020); and is specified by the International Organization for Standardization (ISO) as a normative reference for measuring standardized cooking power for solar cookers in the ISO 19867-1:2018 standard for laboratory testing of cookstoves (International Organization for Standardization, 2018) and in the ISO 19869:2019 standard for field testing of cookstoves (International Organization at the Clean Cooking Alliance. SCI's PEP automates the ASAE S580.1 protocol to determine a performance metric according to the ISO standards mentioned above. Those ISO standards include protocols for durability and safety metrics that apply to solar cookers.

The ASAE S580.1 protocol for evaluating solar cookers provides a single measure of performance: the standardized cooking power, $P_{s(50)}$, expressed in watts. This value for standardized cooking power is evaluated when the cooking temperature is 50 °C above ambient temperature, at a temperature relevant to the onset of cooking. Standardized cooking power is derived from measurements of temperature change in an amount of water proportional to a cooker's intercept area (7000 g/m²); hence, it is a measure of the uptake of power in water that is within a cooking vessel and can be interpreted as a heating rate for a given quantity of water. Standardized cooking power results are normalized using incident solar radiation, allowing comparable results

independent of testing date and location. The testing protocol includes constraints on ambient temperature and wind speed values to limit heat loss due to those factors.

SCI added several refinements in applying the ASAE protocol to improve solar cooker evaluations. These steps are described further in the methodology section below and include using an automated data acquisition platform, on-board and post-processing routines, Global Positioning System (GPS), horizontal pyranometer positioning with trigonometric evaluation of irradiance values, a trigonometric correction of the solar cooker intercept area, default cookware, feed-through thermocouples and a thermocouple calibration routine, and emphasis on using a level surface while testing.

To summarize the ASAE S580.1 protocol, it first calculates the cooking power for a solar cooker during successive 10-minute intervals using equation 1 (eq. 1), where, for each i^{th} 10-minute interval, P_i is the cooking power (W); T_1 is the initial temperature (°C); T_2 is the final water temperature (°C); M is water mass (kg); and C_v is heat capacity of water (4186 J/[kg °C]).

$$P_i = \frac{(T_2 - T_1)MC_{\nu}}{600 \, s} \tag{eq. 1}$$

Adjusted cooking power, P_s , for each 10-minute interval is corrected and normalized to a standard insolation of 700 W/m² by multiplying cooking power P_i by 700 and dividing by the interval average insolation I_i , as shown in equation 2 (eq. 2). The term insolation is used interchangeably with irradiance in this article.

$$P_{s} = P_{i} \left(\frac{700 W/m^{2}}{I_{i}}\right) \tag{eq. 2}$$

Adjusted cooking power values are then graphed with respect to temperature difference between the water and the ambient air – a minimum of 30 adjusted cooking power values (observations) are required. Standardized cooking power, $P_{s(50)}$ (W), the single measure of performance for a solar cooker, is determined where a linear regression fit to adjusted cooking power values crosses the temperature-difference value of 50 °C. This method for determining standardized cooking power is explained further below (Findings and discussion), and shown in Fig. 6.

3. Methodology

With the ASAE S580.1 available as an internationally-agreed-upon standard for testing solar cookers, a corresponding need was for standard instrumentation with consistent components for automating the protocol. A standard test platform with consistency in instrumentation and post-processing routines can provide uniformity in data acquisition. SCI therefore developed a common test platform to facilitate consistent data collection and analysis. SCI self-imposed the following design requirements when developing PEP test stations: the instrumentation should be robust and relatively inexpensive. SCI met these requirements. The PEP test station is robust: it is portable (fits inside carry-on luggage), easy to set up, powered at the test site, and able to withstand most test environments. The PEP test station is relatively inexpensive; its design includes Arduino electronics and requires minimal software programing skills. SCI has designed and created such PEP test stations that: 1) automate the ASAE S580.1 protocol for evaluating solar cookers, and 2) satisfy all the design requirements.

3.1. Hardware

After considering the cost advantages from a do-it-yourself approach, each PEP test station (see Figure 1) was built using commercially available components with a total parts cost of less than 1,000 USD. Test station hardware includes an Arduino Mega open-source electronics platform, GPS, liquid crystal display, three type K thermocouples with controllers, an anemometer (Adafruit, New York, New York, USA), and an SP-215 amplified pyranometer (Apogee Instruments, Inc., Logan, Utah, USA). Electronics are housed in a weather-resistant enclosure and data are stored on a removable SD card; see Figure 2. The pyranometer mounts to a horizontal, bubble-leveled plane, as suggested by the manufacturer; the PEP test station is in the same proximity as the solar cooker(s) being tested, and testing sites are clear of nearby objects that could create shadows and/or reflections. While this positioning differs from the sun-angle alignment suggested in the ASAE protocol, software based trigonometric corrections to SCI solar irradiance measurements give accurate results within instrument tolerance, for solar irradiance incident on solar cookers being tested. The ASAE protocol

allows changes in approach, such as this, if they are notated in the results report. The system is expandable and can accommodate up to eight thermocouples and Bluetooth connectivity.



Fig. 1: Picture from 2 July 2020 of an SCI PEP test station while evaluating the thermal performance of an SCI CooKit, a reflective-panel cooker, using Pyrex bowls as a greenhouse.



Fig. 2. Picture showing the electronics layout for an SCI PEP test station with a close-up of the LCD display (lower right corner).

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3.2. Software

Control software for the PEP test stations was written in-house using C++. The software accepts user input listed in a config.txt file with parameters, such as duration of evaluation, duration of observation intervals, average sun elevation during the test, and water load values. Data is stored on an SD Card as a space delimited text file. This approach automates data acquisition from all sensors. Raw data is post processed by an external program written in C++, including bounded Adjusted Cooking Power calculations according to the ASAE S580.1 protocol. It also applies a 2-point calibration correction to the thermocouple sensor channels to ensure accurate temperature readings. After a solar cooker evaluation, the user can open the resulting data and post-processed files into Microsoft Excel, for example, to inspect the data and prepare graphs for a PEP results report.

3.3. Testing

SCI's PEP requires several set-up steps. First, since the water load for a PEP test is proportional to the intercept area of a solar cooker, one needs to determine that area prior to the test. If the maximum intercept area and the elevation angle for the solar cooker are known, one can apply a trigonometric correction with respect to the sun elevation angle to determine the effective intercept area of the solar cooker for a specific test date and location. When those values are unknown, one can use a photographic approach to calculate the applicable aperture area of a solar cooker for a specific sun elevation angle (Müller, 2022). This approach can also be used to determine the maximum intercept area. After determining the solar cooker form a reasonable distance (about 5 meters; to minimize spatial distortions) along a line parallel to the solar cooker elevation angle, as shown in Figure 3. Then, load the picture into a computer program for Binary Large Object (BLOB) analysis or into a computer application, such as Microsoft PowerPoint, where one can superimpose and tile geometric shapes (with areas scaled according to size of cooker) over the entire intercept area and sum the areas of those shapes to obtain the maximum intercept area.



Fig. 3. Schematic of a solar cooker side view, in blue, and reference lines, in gray, for determining the solar cooker elevation angle (gray arrows).

PEP results apply to an entire solar cooking system, which is the solar cooker and the cookware or cooking pot. Since cookware and cookware material can impact PEP results, it is important to use the same type of

cookware consistently throughout a PEP test of a solar cooker. When conducting PEP tests, SCI prefers to use cookware provided by a solar cooker manufacturer; however, while some manufacturers include cookware with their solar cookers, others do not. SCI chose Graniteware as default cookware for PEP for solar cookers that do not include cookware. Graniteware is commonly available worldwide and often used for solar cooking. SCI testing centers in California, USA and New York, USA both have a set of Graniteware pots and select a best match of pot size to the amount of water needed for the PEP. In its PEP results reports, SCI specifies what cookware was used during each test.

The SCI testing centers favor using a feed-through thermocouple probe mounted to a hole drilled near the center of a cookware lid to reduce thermal leakage during a test. Further steps required for a PEP test are to load 7000 grams of water per square meter intercept area. One should use a scale to weigh the water load to the nearest gram. Also, the PEP test operator should use a leveling device to ensure a level surface for the test and use a consistent tracking time interval, such as 20 minutes.

4. Findings and discussion

Numerous tests across different types of solar cookers conducted since 2017 using the SCI PEP test stations at SCI testing centers in California, USA and in New York, USA indicated that results are repeatable with close correlation between the two locations, thus validating the test platform prior to SCI officially launching its PEP testing program for solar cookers.

Presented here are PEP results acquired at the SCI testing location in New York, USA during 26 May, 8 June, and 2 July 2020 for the following solar cooking system: CooKit reflective-panel solar cooker with a 4-quart Graniteware cooking vessel placed in a Pyrex greenhouse. The PEP test station recorded temperatures, solar irradiance, wind speed and GPS location to a space delimited file on an SD card for later post-processing. Graphical versions of data acquired by the SCI PEP test station include temperature profiles shown in Figure 4 and irradiance and wind speed profiles shown in Figure 5. Adjusted cooking power values are shown in Figure 6 along with the standardized cooking power.



Fig. 4. Temperature profile of 3.256 liters of water (in red) and ambient air (in blue) recorded by an SCI PEP test station on 2 July 2020 while monitoring a CooKit reflective-panel solar cooker with a 4-quart Graniteware cooking vessel placed in a Pyrex greenhouse.





The linear regression fit to the adjusted cooking power values results in a linear equation that can be evaluated for any temperature difference. In the example shown in Figure 6, the regression line equation y = -0.5653x + 86.221. When the regression line for this example is evaluated for x at a temperature difference of 50 degrees C, the resulting standardized cooking power is 58 W, which is the uptake of power into the medium being heated (water). The fundamental definition of power can be expressed as energy per time, and since heat is a form of energy (thermal energy), the standardized cooking power can be interpreted simply as a heating rate for the specified amount of water used during the test, when the temperature difference is 50 degrees C.

SCI PEP results for which manufacturers have given written permission for SCI to publish on the SCI website are summarized alphabetically by solar cooker name in Table 1 (Solar Cookers International, 2022). The PEP results presented here were current at the time of submitting this manuscript (October 2021). Manufactures may improve products or develop new products, and arrange for follow-up PEP tests with SCI. Additionally, other manufacturers may agree to PEP testing at any time. Updated and most current PEP results are available on the SCI webpage for PEP results (Solar Cookers International, 2022).

Solar Cooker Name	Manufacturer	Solar Cooker Type	Standardized Cooking Power (watts)
CooKit with oven bag greenhouse	CooKit	Reflective panel	46
CooKit with Pyrex bowl greenhouse	CooKit	Reflective panel	58
Fornelia Mini	Fornelia	Evacuated tube	93
Glenergy Solar Cooker	Glenergy	Evacuated tube	85
GoSun Sizzle	GoSun	Evacuated tube	99
Haines 1	Haines Solar Cookers	Reflective panel	41
Haines 2.0	Haines Solar Cookers	Reflective panel	82
StarFlower	Solar Chef International	Box oven	117
SunFocus	Sun BD Corporation	Box oven	52
SurviveIt2	SurviveIt2 LLC	Evacuated tube	24
UGLI	Sun BD Corporation	Box oven	61

Table 1: Summary of SCI PEP results for solar cookers

In obtaining the standardized cooking power, the regression line also provides two additional aspects of the solar cooker: 1) the heat loss coefficient (the slope), and the initial cooking power (the y-intercept). These values suggest the insulation quality and there is potential for correlating these values with different types of solar cookers (Funk, 2000) (Ebersviller & Jetter, 2020). These values are provided in all SCI PEP reports via the regression equation, which can also provide guidance for solar cooker designers and manufacturers to meet their goals.

In addition to measuring standardized cooking power (in watts), PEP results suggest design-based aspects that can improve performance: 1) use a larger collector for gathering more incident solar energy – there is a general trend that standardized cooking power scales with intercept area, and 2) give attention to cookware and greenhouse material, as they are a part of the entire solar cooking system being PEP tested. Regarding greenhouse material, for instance, it may be desirable to use a clamshell of two 4-quart Pyrex bowls instead of a plastic bag as a greenhouse for reflective-panel solar cookers such as the CooKit. The transmission spectrum for Pyrex (Präzisions Glas & Optik, 2022) shows that it has high transmission for visible light - it lets sunlight in - and poor transmission for infrared light emitted from a hot black-body irradiator - it blocks heat radiation from a cooking pot from escaping (File:BlackbodySpectrum loglog 150dpi en.png, 2022). While transparent plastic bags can also have optical spectra favorable for solar cooking, surface topology and material overlap for plastic-bag greenhouses can reduce incident sunlight transmission. Furthermore, designers should evaluate aspects about materials regarding sustainability, durability, expected lifetime, insulation quality, ease of use and transport, cost, and availability. For example, plastic bags are banned in some countries. PEP results can also help inform consumers and users to choose design characteristics suitable for the types of food and the desired cooking times that they would like.


Fig. 7. The SCI PEP tested label, which solar cooker manufacturers can associate with their PEP-tested products and gain recognition for having product tested by an independent organization and according to ISO standards.

SCI generated its first official PEP results reports during 2019 and SCI's testing program has been gathering momentum along several fronts: with manufacturers, with national policymakers and with solar cooks. The steps for completing a PEP testing cycle involve: 1) manufacturer arranges for PEP testing by SCI with a signed agreement; 2) SCI conducts PEP testing of a like-new model of the manufacturer's solar cooker at one of SCI's testing locations; 3) SCI prepares a PEP results report and sends it to the manufacturer; 4) pending manufacturer approval of the PEP results report, manufacturer signs an agreement with SCI for SCI to publish their PEP results; and 5) SCI publishes the PEP results and manufacturer gains use of SCI's PEP tested label, shown in Figure 7. Furthermore, SCI showcases PEP-tested solar cookers as part of its advocacy efforts for example, at the United Nations, which dovetails with SCI's efforts in strengthening the capacity for solar cooking worldwide.

5. Conclusion

SCI has developed, built and implemented four PEP test stations for acquiring data to measure the thermal performance of solar cookers according to ISO standards at SCI testing centers in California, USA, in New York, USA, in Lalitpur, Nepal, and in Nairobi, Kenya. SCI developed several refinements in applying the ASAE S580.1 protocol, including using an automated data acquisition platform, on-board and post-processing routines, GPS, horizontal pyranometer positioning with trigonometric evaluation of irradiance values, a trigonometric correction of the solar cooker intercept area, default cookware, feed-through thermocouples and a thermocouple calibration routine, and emphasis on using a level surface while testing. SCI posts PEP results and reports on its website following approval and permission by respective solar cooker manufacturers.

Manufacturers are encouraged to have their solar cookers PEP tested by SCI. PEP results can have a role in design optimization and product improvements. SCI also suggests that manufacturers post PEP results in terms of the standardized cooking power (in watts) as performance specifications for their products. Standardized cooking power values can help consumers, project leaders and national policy makers decide which solar cookers to invest in. SCI also encourages individuals, organizations and governments to invest in solar cooking,

which can increase cooking-energy independence and food security. Investment in solar cooking can also help with climate change mitigation and adaptation, and it can be particularly beneficial with overcoming social stressors linked with global pandemics and internal displacement.

SCI hosts a global evidence base for solar cookers that can be viewed as a map of the worldwide distribution of solar cookers (Solar Cookers International, 2022). The map is interactive, where a user can obtain details such as number of cookers, implementing organization, and location. SCI encourages the solar cooking sector to post its distribution data – quantity, type, and approximate location – to further this evidence base. SCI shares this evidence with policy makers and the public to demonstrate the advantages of solar cooking. This information has also informed the creation of SCI's Economic Impact Summaries, a country-by-country analysis of the estimated to-date and potential environmental, health, and economic benefits of solar cooking on SCI's website (Solar Cookers International, 2022).

PEP results have potential to add another dimension to this evidence base, which is to produce a global distribution of installed solar cooking capacity (in watts) per nation. A map view of the installed solar cooker capacity could inspire more innovation and competition among nations to increase their solar cooking capacity.

Furthermore, PEP results increase the accountability and the credibility of the solar cooking sector. Solar cooking is an innovative, inclusive, and cross-cutting solution that helps to achieve all 17 United Nations SDGs. It is an affordable, accessible, clean and sustainable cooking solution for reducing CO₂ and black carbon emissions; hence, solar cooking is a readily available approach that national leaders can include in their plans to reduce emissions, such as their Nationally Determined Contributions (NDCs), which are part of the Paris Agreement within the United Nations Framework Convention on Climate Change. In the context of global efforts, such as those at the United Nations level, PEP results for solar cooker performance specifications can help unlock funding pathways for large-scale solar cooking opportunities that can enhance the economic impact from solar cooking at the national level (Solar Cookers International, 2022).

6. Acknowledgements

Solar Cookers International would like to thank all of its current and previous donors, volunteers, board members, and staff who have supported and encouraged SCI's PEP development and implementation including former SCI Executive Director Julie Greene. SCI thanks SCI Research Specialist Justin Tabatchnick for designing and building the hardware and software for the PEP test stations. SCI thanks SCI Global Advisor Paul Funk for his role in authoring the ASAE S580.1 protocol and for continuing to share his expertise in applying the ASAE protocol. The authors had productive exchanges with Paul Arveson at Solar Household Energy, which helped move this work forward. SCI thanks Ranyee Chiang, who, from her former role at the Global Alliance for Clean Cookstoves (now the Clean Cooking Alliance) suggested that SCI develop testing protocol that harmonized with ISO standards. SCI thanks James Jetter at the Environmental Protection Agency for his contributions to solar cooker evaluations and for his leadership at the ISO Technical Committee 285, which has developed standards for evaluating clean cookstoves. Approval and support were expressed by participants at SCI meetings, such as the 6th SCI World Conference held at the Muni Seva Ashram in Gujarat, India in January 2017. SCI thanks the SCI Associates, manufacturers, and collaborators worldwide who understand the importance of measuring impact and contributing their valuable insight to increase global understanding of the positive impact of solar cooking for all.

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Direct and mixed solar drying effect on edamame (Glycine max (L.) Merr.) kinetics and colorimetry

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Abstract

Edamame is food with valuable nutritional content, mainly due to its high protein and vitamin content. Given today's fast-paced lifestyle, dehydrated foods have become a significant option to obtain the necessary nutritional contributions. This study reports edamame drying in a mixed solar dryer (MSD) and a direct cabinet-type solar dryer (DSD). As quality parameters, colorimetric data, proteins, and initial and final water activity were obtained. According to the results, the equilibrium moisture content was reached faster in the MSD, with 6 hours; the maximum drying velocity achieved for this technology was 0.0109 kg water kg dry matter min with a final moisture content of 0.6369 g water / g dry matter. In addition, the content and the total color change (ΔE) were improved in the MSD. The mathematical model that best adjusted to the experimental results in both technologies was the Weibull with a minimum R² of 0.9947. Solar drying is a feasible technology to conserve edamame, reduce greenhouse gas emissions, food waste, and provide essential nutrients to people's daily diet.

Keywords: Solar dryer, mixed solar dryer, thin layer modeling, colorimetric analysis, food preservation, edamame

1. Introduction

Edamame is the immature soybean (Glycine max (L.) Merrill), harvested as it reaches about 80% of its maturity. It has a yellowish-green color and differs from mature soybeans, usually light brown. (Fehr and Caviness, 1977). Most people have heard of edamame, especially in East Asia, because it provides many nutrients and generates medicinal effects on humans. It is rich in proteins, phosphorus, calcium, iron, vitamins, and dietary fiber; likewise, it prevents and suppresses various cancers due to its high content of isoflavones. Also, it can inhibit the activity of tyrosinase (Coward et al., 1993; Simonne et al., 2000), which causes skin spots that appear on the skin over time; Moreover, it has a positive impact on bone and dental health, reduces the risks of cardiovascular accidents and lowers blood cholesterol (Mentreddy et al., 2002).

Edamame is consumed mainly as a snack and vegetable, complement to soups, or processed into sweets. However, edamame has high water content, stimulating microorganisms' growth and proliferation. This condition results in fast decomposition, so its shelf life is only a few days. As a result, the FAO (Food and Agriculture Organization) data indicate that more than 20% of the harvested cereals is wasted, representing almost 50% of total food losses, generating the most significant contributor of greenhouse gas emissions. (UN and FAO, 2019).

Gradually, hunger and malnutrition are the primary health risk worldwide; around 135 million people suffer from severe hunger, and due to the COVID-19 pandemic, could double this figure and add 130 million more people by the end of 2020(UN and FAO, 2020). Likewise, along with famine, the poor diet of human beings is related. For example, in the last revision in 2018, about 821 million people worldwide suffered from malnutrition, 1 in 10 human beings (UN, 2020a). By 2019 the number of hungry people globally reached 690 million (47.7 million are from Latin America and the Caribbean). Similarly, 205 million people live in conditions with uncertainty about their ability to obtain food, which leads them to reduce the quantity or quality of the food they consume (UN, 2020b).

Given the current lifestyle, the growing demand for edamame worldwide, and its rapid decomposition, measures have been seeking to extend the shelf life. The main proposals to conserve edamame using different methods are a) Freezing by hydro-fluidization. In this method, concentrated aqueous solutions are used at low temperature as a cooling medium pumping it upwards through holes in the refrigeration vessel to generate jets of liquid that preserve the agitation of the refrigerant that creates high surface transfer coefficients (Fatahillah et al., 2019; Juan Manuel Peralta, 2009). b) Blanching in mesh bags in hot water (at 100°C) combined with cooling storage (4°C) or freezing (-20°C) (ChunQuan et al., 2012). c) Freezing drying or lyophilization combined with the bleaching with a steam of the fresh edamame(Kamila et al., 2019).

However, dehydration is an efficient method to remove water by evaporation from most products. The reduction of moisture content inhibits and decreases microbial and enzymatic activity, advantageous for long-term preservation. Few have studied the conservation of edamame using dehydration methods, as in Qing-guo et al. (2006). They used microwave drying, vacuum with pulse jet, vacuum, and hot air drying to determine the microstructure, color, texture, and taste of edamame; Also, Hu et al. (2007) conducted vacuum microwave drying (VMW) to investigate and compare drying velocity, final moisture content, and dry product quality between the different heights of edamame in a deep bed. However, these works used conventional technologies with high energy consumption and high costs for their use.

Despite a large amount of information on the freezing of edamame using various methods, the information related to drying or dehydrating is scarce. In addition, there is a lack of studies on drying using solar energy. It is important to remember that developing energy-efficient technics is essential to solving complex environmental problems (Castillo-Téllez et al., 2020).

2. Methods

Raw material

Immature soybeans (Glycine max (L.) Merr.), grown in northern China, near the border with Russia, were selected. First, the edamame beans were separated to obtain a homogeneous group, depending on the size and color. Then, they were washed and weighed. The weight of each bean ranged from .95 to 1.00 grams. The experimentation was performed during three sunny days with very casual small clouds in Xochitepec, Mor., México. The experiment was carried out in triplicate.

In this work, the drying process of the edamame was carried out experimentally using a cabinet dryer and a mixed-type solar dryer.

Direct solar dryer cabinet type

The equipment consists of: a drying chamber of 44 liters with measures of 35x64x26 cm with transparent polycarbonate cover, two aluminum trays with $.30 \text{ m}^2$ of total drying area, humidity (%) and temperature sensors (°C) and inside the drying chamber a perforated tray with an area of 0.0468 m² was placed. Heat transfer was by natural convection.



Fig. 1 Direct solar dryer

Mixed solar dryer

The MSD contains three main parts: 1) A flat solar collector heating the air by natural convection, 2) a drying chamber of 0.038 m^3 with eight trays located in 4 vertical levels. The total drying area is 0.52 m^2 , allowing solar radiation passage through a transparent polycarbonate cover. Its side walls are insulated with a polyisocyanurate plate 1.27 cm thick. 3) A chimney where moist air from the drying chamber can be extracted (López-Vidaña et al., 2020).



Fig. 2: Mixed solar dryer

Instrumentation

Operation parameters

Humidity: To determine the moisture of edamame beans, two moisture analyzers, Sartorius MA 45 and Ohaus MB45, were used with an accuracy of $\pm 0.01\%$ mg. The sample of approximately 1 gram was placed in the analyzer. This procedure was performed before starting and at the end of drying.

Water activity (a_w): Water activity is the parameter that determines the stability of the food concerning ambient humidity, and the fresh and dry edamame was measured before and after the drying process. A portable computer, Rotronic HygroPalm, was used with an accuracy of $\pm 0.01\%$. Mg. An average of three measurements was reported at room temperature of 26.5 $\pm 1^{\circ}$ C).

Temperature: It was measured by type K thermocouple, previously calibrated using an Ameter Jofra Instruments temperature calibrator, model D55SE, in a range of 10°C to -12°C and accuracy of ± 0.04 °C.

Weight: Weight measurements were determined by Ohaus' Adventure balance model with an accuracy of ± 0.001 grams.

Colorimetry: A colorimeter model PCE-CSM 5 previously calibrated for high-precision quality control using the CIELAB color space was used.

Mathematical modeling

The models applied in this study are shown in Table 1. The dimensionless MR (moisture ratio) is a function of drying time and is calculated as (Toĝrul and Pehlivan, 2004):

$$MR = \frac{M_c - M_e}{M_0 - M_e} \tag{eq. 1}$$

Where Mc is the moisture content, Me is the equilibrium moisture content, and Mo is the initial moisture.

The equilibrium moisture content Me was determined by the equation y, (Castro-Muñoz and Nieves-Segura, 2018):

$$Me = \frac{W_1 Mo + W_f W_1}{W_1 (1 - M)}$$
(eq. 2)

 M_e , expressed in (kg water/kg dry matter), W_1 is the initial weight, M_0 is the initial moisture of the samples, and W_f is the weight of the sample at M_e .

This ratio was adjusted to the five thin layer drying models shown in Table 1. The model that best describes the experimental data was analyzed according to the Root Mean Square Error (RMSE), chi-square (χ^2), and correlation coefficient (\mathbb{R}^2).

Name	Model	Reference
Newton	MR = exp(-kt)	(Liu and Bakker-Arkema, 1997)
Page	$MR = exp(-kt^n)$	(Page, 1949)
Modified Page	$MR = exp(-(kt)^n)$	(White et al., 1981)
Henderson and Pabis	$MR = a \exp(-kt)$	(Henderson and Pabis, 1961)
Logarithmic	$MR = a \exp(-kt) + c$	(Toğrul, 2005)
Wang y Singh	$MR = 1 + at + bt^2$	(Wang and Singh, 1978)
Weibull	$MR = exp \ (-\frac{t}{\beta})^{\alpha}$	(Tzempelikos et al., 2015)

Tab. 1: Thin-film models applied to dry kinetics.

3. Results and discussion

Samples' initial moisture content was 70% and water activity (a_w) of 0.95. At the end of drying, the water activity decreased to 0.35, which ensures the safety of the food. The maximum ambient temperature and humidity reached 37 °C and 70% in the experimentation days, respectively. The DSD reached a temperature of 59 °C inside the drying chamber, while the MSD reached 78 °C and minimum humidity of 25% and 12%, respectively (Figure 3).



Fig. 3: Temperatures and Relative humidities reached in dryers

Higher temperatures and lower relative humidity are essential factors to reduce drying times, providing adequate conditions to facilitate moisture extraction from the food (Jorge de Jesús et al., 2021).



Fig. 4: Moisture content evolution during drying

The moisture content was recorded during edamame drying. In Figure 4, the moisture content reduction during the drying kinetics can be observed. The graph shows that the MSD minimizes the time to reach equilibrium moisture content (the vapor pressure of the water held by a product is equal to the water vapor pressure of the surrounding air (Yaciuk, 1981)). In this dryer, only 380 min was required to finish the drying. On the other hand, the DSD needed 490 min. This time reduction is due to the higher temperatures and humid conditions inside the MSD chamber, allowing the drying process to be more efficient and consequently helping producers obtain higher economic profits.

The drying rate curves did not show any period of constant velocity in the DSD, while, in the MSD, an increase in the rate can be observed towards the end of the kinetics. Even though at the beginning of the kinetics, the drying velocity was higher in the DSD, the slope of the drying velocity curve of the MSD remained more constant during the process. (See Fig. 5)



Fig. 5: Drying rates of edamame, with both technologies.

Figure 6 shows the moisture ratio (MR) versus the drying time. The solid lines correspond to both solar technologies' experimental results (MR). As can be seen, most of the models present a good fit with these results. However, the mathematical that best represents all cases' experimental results, with an $R^2 > 0.99$, is Weibull. Therefore, this model can predict the kinetics of solar drying of edamame under experimental conditions.



Fig. 6: Drying adjustment charts for both technologies

Table 2 shows the adjustment parameters and statistical data obtained for all analyzed models. Results illustrate that the best model describing edamame kinetics is Weibull for both experimental technologies because it presents higher R^2 and minimum X^2 and RMSE. Consequently, this model can be used to predict edamame drying.

Direct Solar Dryer			Mixed Sola	ar Dryei	•
Weibull	а	1.20E-02	Henderson and Pabis	а	1.6393
	b	-1.3083		k	0.4921
	k	0.2746		\mathbb{R}^2	0.9921
	n	1.5965		RMSE	0.0292
	\mathbb{R}^2	0.9947		\mathbf{X}^2	0.0012
	RMSE	0.0236	Weibull	а	-0.9769
	X^2	0.0010		b	-8.5077
Logarithmic	a	1.9079		k	1.4603
	c	-1.76E-02		n	0.2035
	k	0.6111		\mathbb{R}^2	0.9988
	\mathbb{R}^2	0.9913		RMSE	0.0115
	RMSE	0.0304		\mathbf{X}^2	0.0003
	\mathbf{X}^2	0.0012		а	1.6019
Henderson and Pabis	a	1.9429	Logarithmic	c	-8.40E-02
	k	0.6428		k	0.4026
	\mathbb{R}^2	0.9904		\mathbb{R}^2	0.9965
	RMSE	0.0320		RMSE	0.0192
	X^2	0.0013		X^2	0.0006

Tab. 2 Modelling parameters

Table 3 shows a,b, and L parameters before and after the procedures. During the drying process, these parameters changed depending on the dryer used. It can be seen that solar drying presents good color preservation in edamame.

		5	5
LAB	Fresh edamame	Direct Solar Dryer	Mixed Solar Dryer
L*	40.04	50.69	48.9
a*	-4.65	1.43	2.36
b*	19.33	23.5	19.11

Tab. 3 Color change in both technologies

As shown in Figure 7, the ΔE is very similar in both cases and very close to the commercially accepted values. However, the Chroma is higher on the DSD. Therefore, the MSD preserves better edamame color because prolonged exposure to sunlight decreases the product's quality in the DSD. However, a significant difference in ΔE is not desirable because consumers prefer products that resemble the color of the fresh product before drying. In addition, a considerable color difference shows a higher degree of browning, which could be unattractive in appearance. According to the literature, when the final product has a value of up to 3, the color difference results appreciably (Hii and Law, 2010). Moreover, as the color change between raw and dry products is more significant, nutrients' degradation is higher.



Fig. 7: Delta E and resulting Chroma in both technologies.

4. Conclusions

Two solar drying technologies were applied to edamame preservation. The results show that both technologies are technically feasible for this process. In addition, the kinetics, colorimetry, and models during edamame drying were analyzed. According to the findings, the hybrid solar dryer technology provided a shorter drying time, higher drying rates, and better color preservation. The drying time needed to reach equilibrium moisture for the MSD was 380 min with an ΔE value of 11.03, which is commercially acceptable. However, DSD can be used with competitive results.

Moreover, the Weibull model was better adjusted to the drying kinetics. Therefore this model can be used to design and size solar dryers. Solar drying is a sustainable solution for edamame conservation.

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Optical Evaluation of the Tolokatsin-2020 High-Efficiency Solar Cooker

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Abstract

In order to cook with solar energy, it is necessary to have a highly efficient solar cooker that captures a great portion of the diffuse radiation. More than 20 years ago, the first solar cookers called "Tolokatsin" (Náhuatl language name meaning "born in Toluca", the city in which they were created) were designed. Nowadays, the Tolokatsin solar cookers work with a three-dimensional multi-compounded solar concentrator based on non-imaging optics, using only mirrors of simple curvature. The original design consists of a concentrator with four pairs of optimally truncated mirrors that allow an excellent operational performance. A further advance has been made to reduce the losses by reflections, by changing the number of mirrors and the solar concentration as predicted recently by constructal law, keeping only mirrors of simple curvature; demonstrated by ray-tracing techniques, where the validation of the new design can be addressed since the optical efficiency was increased 9.4%.

Keywords: optical efficiency, solar cooker, Tolokatsin, ray-tracing

1. Introduction

The world has a serious urgency to provide the necessary resources and means to combat famine, as UN reports estimate that there are around 690 million people in the world suffering from food shortages (United Nations, 2020), and also to drastically reduce the consumption of fossil fuels for cooking. Cooking is a basic need for everyone, practiced everywhere by humankind, and a heat source above 100 °C is needed (Lecuona et al., 2017). Around 28 million Mexicans depend on burning solids for food cooking, usually firewood or charcoal, (globally there are about 3 billion people who eat food cooked with firewood according to the International Energy Agency) (IEA. International Energy Agency, 2018; Rincón Mejía, 2010). Cooking burning any kind of fuel, lead to some problems that must be addressed as body burns, explosions, poisonings, and contamination, just to mention a few, resulting in approximately 3.8 million deaths per year attributable just to household air pollution (World Health Organization, 2018).

For years, the implementation of solar cookers and solar ovens has allowed us to tackle the after-mentioned problems by reducing considerably the burning of any fuel, improving people's quality of life regardless of their age range. Allowing people to cook their food without having to depend on fuels that have an inherent cost and that for the population that is in poverty, the dilemma arises of prioritizing the needs to be covered.

At present, there are a large number of alternatives for cooking with the Sun, from simple devices such as the "box solar cooker", or the implementation of medium concentration systems such as parabolic troughs and parabolic dishes, or even large Fresnel lenses for cooking at higher temperatures (Lecuona et al., 2017; SCI, 2019). These systems present certain problems that have been tried to overcome, such as the implementation of low concentration ratio systems, like the solar panel cookers, "funnel" and its modifications developed by Ruivio (Apaolaza-Pagoaga et al., 2021; Solar Cookers International, n.d.), or even higher concentration ratios as Coccia et al. (Coccia et al., 2017). Some examples of these systems are shown in Fig. 1.



Fig. 1: Main types of solar cookers (González-Mora, 2021). Adapted from: (Solar Cookers International, 2019)

Considering this, the Tolokatsin solar ovens (meaning "born in Toluca" – the city in which they are from – in Náhuatl,) were first designed and built more than 20 years ago. The main difference between the Tolokatsin solar oven with the many other devices designed to cook with the Sun is the use of non-imaging optics that lead to an efficient radiation transfer from the source (Sun) to the objective (receiver). This results in a compact multi-compound system that can achieve high temperatures in little time and with high efficiency (González-Mora et al., 2020; Winston et al., 2005). The direct application of non-imaging optics allowed the applications of Tolokatsin to be extended to other sectors as solar sterilizing (González Mora et al., 2016a, 2016b), diversifying the original line of its design with great success.

1.1. Structure and scope

Recently, authors have predicted that decreasing the number of reflections in the Tolokatsin designs will lead to an optical efficiency increase (González-Mora et al., 2020), so an optical ray-tracing was needed to verify this claim. In the present, optical analysis of the new Tolokatsin-2020 design is performed with ray-tracing software to validate the new design. The Tolokatsin designs have evolved through the years tackling a considerable reduction of the optical losses, keeping in mind the high efficiency and easy manufacturing processes. Section 2 includes a brief description of the Tolokatsin designs, while Section 3 describes the general procedure for the optical analysis with a brief discussion of the results. The present analysis can be used for further thermal analysis to quantify the figures of merit F_1 and F_2 (Collares-Pereira et al., 2018; Funk and Larson, 1998; Funk, 2000) for this solar cooker design.

2. Tolokatsin designs

The Tolokatsin solar ovens take advantage of non-imaging optics, where efficient radiation transfer from the source to the objective (receiver) can be accomplished (Winston et al., 2020, 2005), even though sacrificing the sun image (aberration formations). The geometries for all Tolokatsin designs are principally a proper combination of flat in the upper part (Eq. 1) and circular absorber for the lower part (Eq. 2) CPCs profiles, taking into consideration the optimum truncation criterion of three times the acceptance angle, originally stated by Rincón et al. (2009).

$$\begin{cases} x(t) = \frac{(1+\sin\theta_0)\cos t}{1-\sin(t-\theta_0)}\\ y(t) = \frac{(1+\sin\theta_0)\sin t}{1-\sin(t-\theta_0)}, \quad t \in \left(0, \frac{\pi}{2} - 3\theta_0\right) \end{cases}$$
(eq. 1)

$$\begin{cases} x(t) = \sin t - t \cos t \\ y(t) = -(\cos t + t \sin t), & t \in \left(0, \frac{\pi}{2} + \theta_0\right) \\ \begin{cases} x(t) = \frac{\sin \theta_0 \cos(t - \theta_0) - \left(\frac{\pi}{2} + t + \theta_0\right) \cos t}{1 + \sin(t - \theta_0)} + \cos \theta_0 \\ y(t) = \frac{\sin \theta_0 \cos(t - \theta_0) + \left(\frac{\pi}{2} + t + \theta_0\right) \sin t}{1 + \sin(t - \theta_0)} - \sin \theta_0 \end{cases}$$
(eq. 1)

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where θ_0 is the half-acceptance angle of the CPCs and t the parameter that allows plotting the profiles.

Originally, the Tolokatsin design consisted of eight mirrors, distributed in four pairs, as shown in Fig. 2(a) and Fig. 2(b). The designs work properly for cooking at 140 °C, however, during its continuous operation for more than 10 years, it was noted that the optical performance of the system can be increased, keeping the same concentration ratio (2.75x), with less use of mirror and decreasing the optical leakage by using 2 more mirrors, as shown in Fig. 2(c). This was also independently investigated by (Cooper et al., 2013a), where it is shown that the square aperture has some favorable anomalous behavior, validating the use of the 1-dimensional curvature mirrors for a 3D design; although this analysis was for a single-stage concentration system.



(a) Sketch of the original design



(b) Original Tolokatsin

(c) Tolokatsin-V

Fig. 2: Tolokatsin first improvements

2.1. Further improvement of the Tolokatsin solar ovens with the constructal law

Although all the improvements mentioned above have been the result of the continuous use, Gonzalez-Mora et al. (2020) recently demonstrated that with the use of Bejan's constructal law (Bejan and Lorente, 2008; Rocha et al., 2012), it is possible to obtain the same results that were found experimentally, considering that:

"For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed (global) currents that flow through it."

The results of the constructal law applied to the Tolokatsin solar cooker concept led to the following conclusions:

- increase the optical efficiency of the concentrator by reducing the average number of reflections of rays that imping on the absorber
- increase the concentration ratio (and so the stagnation temperature of the absorber)
- improve thermal insulation.

By allowing the design to continue to evolve, in such a way that the concentrated solar radiation passing through the optics of the system reaches the receiver (González-Mora, 2021), it is shown that by increasing the number of mirrors (originally one pair of top mirrors, then two pairs and finally three pairs), it is possible to redirect the

sunlight in a better way by decreasing the average number of reflections; and also to obtain a more homogeneous radiation flux over the absorber, even for the combination of single curvature CPCs, as shown in Fig. 3.



Fig. 3: Tolokatsin-2020 design

3. Optical analysis

While performing the constructal analysis (González-Mora et al., 2020), it was possible not only to validate the truncation criterion that was proposed from a geometrical perspective by Rincón et al. (Rincón Mejía et al., 2009) but also, thermodynamically, by capturing the same amount of energy as a system without truncation; where this energy is given by a relation of the type $Q \sim G_b C_g \eta_o$, where the geometrical concentration $C_g = C_g(\theta)$, and also considering that the optical efficiency is a parameter that depends directly on the average number of reflections N in the optical system by means of a relation $\eta_o \sim \rho^N$.

Originally, the average number of reflections for 2D CPC's without truncation was studied by Rabl (Rabl, 1976), and in (González-Mora et al., 2020) the corresponding analysis have been obtained for the system with truncation, which we can be recalled as an "optimal" value. This analysis has even shown that truncation not only allows a reduction of the mirror quantity, but also the average number of reflections N decreases considerably because this parameter depends directly on the geometrical concentration and the acceptance angle $N = N(C_g, \theta)$. Since no formal optical analysis had been performed for the Tolokatsin solar cookers, there was an urgency to do a ray-tracing procedure, which can validate the results and even, identify future optimizations via the constructal law (González-Mora, 2021).

3.1. Analysis of the Tolokatsin 2020

The Tolokatsin-2020 has a concentration ratio of 5.8x, with a 16.86 cm receiver diameter, and an aperture area of 1.621 m². For the optical evaluation of the new design, a Monte-Carlo ray-tracing scripting procedure was performed in SolTRACE (Wendelin, 2003) with the use of Zernike Polynomials (Doyle et al., 2012) (Eq. 3) to define the surfaces, where $B_{i,j}$ are the coefficients and N the polynomial degree. As data input, the following parameters were considered:

- 0° incidence angle
- The radiation source was modeled as isotopic with 4.65 mrad (pillbox sun shape) and a Gaussian profile with 2.73 mrad
- 0.92 mirror-reflectivity
- 0.94 receiver-absorptivity
- 0.98 glass covers transmissivity
- 3 mrad slope error for the mirrors and 1.95 mrad for the receiver
- 0.5 mrad specularity error
- 1000 W/m² DNI

$$z(x,y) = \sum_{i=0}^{N} \sum_{j=0}^{i} B_{i,j} x^{j} y^{i-j}$$
 (eq. 3)

For the optical simulation, three cases are considered: 1) no optical errors, 2) optical errors and pillbox solar distribution, and 3) optical errors and Gaussian distribution. Each flux map is shown fin Fig. 4. The first case was used to define the peak optical efficiency, while the other two cases the variation of the optical efficiency under construction errors for a more accurate behavior of the real system. In the three cases, similar behavior is noticed even for including/excluding the optical errors and for different sun-shape.



Fig. 4: Tolokatsin-2020 design

The optical efficiency (Eq. 4) is quantified as the ratio of the heat flux reaching the absorber (Q'_{rec}) to the heat flux entering the aperture of the Tolokatsin-2020 $(\dot{Q'}_{ap})$. Table 1 summarizes the results of the optical analysis of each case.

$$\eta_o = \frac{\dot{q'}_{rec}}{\dot{q'}_{ap}}$$
 (eq. 4)

where each heat flux is computed as a function of the number of rays impinging the surfaces and the power per ray. In each case, 10 million rays were used for the analysis; the same number of rays was used by Cooper et al. (2013), enough to obtain an uncertainty of the order of 0.01%.

The similar behavior and optical efficiency of the three cases can be explained by the incompressibility of the sun rays across the optical path in the non-imaging optics system as stated by Fermat's principle and the etendue conservation (Winston et al., 2020).

Parameter	Case 1 (no errors)	Case 2 (pillbox)	Case 3 (Gaussian)
Average flux [W/m2]	3436.32	3434.21	3435.44
Peak flux [W/m2]	17839	16392.9	16372.7
Optical efficiency [%]	81.09	81.03	81.02

Tab. 1: Results of the optical analysis

3.2. Comparison with the Tolokatsin-V

As shown in Fig. 2(b) and Fig. 2(c), the original Tolokatsin design and the Tolokatsin-V have a square-shaped aperture area, while the Tolokatsin-2020 (Fig. 3) has an octagonal shape. To compare the advantage of adding more mirrors, a raytracing of a modified version of the original design and the Tolokatsin-V was performed with the same concentration ratio (5.8X). The heat fluxes on the receiver are displayed in Fig. 5.



Fig. 5: Tolokatsin-V flux map on the receiver

Comparing Figs. 4 and 5, the Tolokatsin-V receptor has a higher radiation peak than the Tolokatsin-2020; however, the flow is less uniform and covers a smaller area. Whit these results, an important result must be addressed, since until now, the use of a collimator inside a concentrating solar cooker was unaware of the main solar-cookers users and designers, since the use of concentrating devices leads to a higher temperature and a time-reduction for cooking is well understood and implemented, so the use of a collimator, which inherently decreases the concentration ratio, seems to be contradictory. However, the underlying objective of including a collimator in the lower part of the design lies in a "trap" for all the photons in a finite-sized zone wrapping the receiver, which is invariant to the sun shape, as can be seen in the flux maps of Fig. 4.

As described previously, the optical efficiency for the Tolokatsin V was quantified at 74.3%. Comparing the results from Table 1 with this design, it can be noticed that the Tolokatsin-2020 increased its optical performance by 9.14%. The improvement of the optical behavior is justified by a considerable reduction in the number of reflections of the sun-light to reach the absorber, as predicted previously with the use of the constructal law (González-Mora et al., 2020), and a better flux distribution on the receiver.

4. Conclusions

It can be seen from the results, that to guarantee excellent performance and great reliability is recommended the systematic application of the constructal theory, as demonstrated easily by González-Mora et al. (2020), and validated with the +25 years of continuous operation and some improvements of the Tolokatsin designs; however, until now, no formal optical analysis over the Tolokatsin designs was performed.

The optical efficiency of the Tolokatsin designs has been determined, where it is demonstrated that the increase in the number of upper-mirrors, led to an increase of the efficiency, from 74.3% of the Tolokatsin-V to 81% in the Tolokatsin-2020. However, a drawback must be noticed since the new sophisticated design has a greater manufacturing complexity and costs.

The 9.4% optical efficiency increase can be explained by the use of a collimator in the lower part of the system,

and the reduction of the number of reflections, resulting in better flux patter onto the receiver. The collimator generates a "photon trap", where all the light reaching the collimator's aperture is finally redirected to the absorber. The reduction of the number of reflections was achieved with the "optimal" truncation criterion, as demonstrated in previous work (González-Mora et al., 2020), and validated with the ray-tracing procedure.

With the optical analysis been performed, a formal thermal analysis can be done in future works to quantify the figures of merit F_1 and F_2 , and the standardized power. This would lead to a full characterization of the Tolokatsin-2020 design, and with further constructal analysis, the possibility of identifying new opportunities to improve the solar energy transfer to the receiver and cook in a better way.

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A Techno-Economic Analysis of Solar Injera Baking Systems

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Abstract

The energy supply in Ethiopia is dominated by biomass energy, mainly for household consumption. A survey of 721 Ethiopian urban households presented here shows that about 55% of the household energy consumption is spent on cooking and additionally 37% is spent on baking. The final energy consumption per household yields about 8.8 MWh per year, which is quite high regarding the fact that no space heating is needed. Thus, solar cooking is crucial for CO_2 emissions reduction, and to limit deforestation and occurrence of health incidents related to cooking with biomass in Ethiopia.

Further, the paper presents an economic analysis of an advanced steam-based concentrating solar *Injera* baking stove that allows for indoor cooking. Despite the high investment costs of the solar stove, the levelized costs of useful heat, LCoE_{useful}, determined for a life span of 20 years turn out to be about 60% lower than the LCoE_{useful} for baking with a typical biomass *Mirt* stove for the selected reference conditions in this case study.

Keywords: Ethiopia, end-use consumption share, solar Injera baking system, economic comparison

1. Introduction

The burning of collected fuelwood contributed 19.4% to the annual CO_{2e} emissions from agriculture and forestry and 17% to the overall annual CO_{2e} emissions in 2010 in Ethiopia. The strong dependence on burning biomass for cooking results in deforestation, fuelwood scarcity, and indoor air pollution. On top of that, diseases and health incidents due to biomass combustion for cooking are serious concerns especially in rural households as the kitchen and living room are usually the same. LaFave et al. (2021) attest that indoor cooking is accountable for the increased occurrence of respiratory infections, inveterate obstructive pulmonary disease, cataracts, and cardiovascular illnesses.

The residential sector electricity consumption, a large consumer compared to other sectors in Ethiopia, reached 4.2 TWh in 2018, which represents 46% of the total power consumption of the country. Another paper depicts that about 7% of the total national electricity consumption is used for *Injera* baking (Liyew et al., 2021). *Injera* is a spongy flatbread and staple food in Ethiopia, Eritrea, and Somalia. It is the main dish of these countries usually consumed with "wot" (Neela and Fanta, 2020). Wot is a traditional sauce made by boiling a mixture of either vegetables, meat, or cereals flour with different spices and additives.

Solar cooking technologies have the potential to reduce the use of biomass in the residential sector significantly given the ample solar irradiation throughout Ethiopia (Bayray et al., 2021). However, there are a wide variety of technical and economic barriers to the penetration of solar cookers, although many technologies have been developed during recent years, referred for example in Adem and Ambie (2017). Some studies also report that the cost of solar energy technologies is falling and the rate of adoption by rural households is increasing. Nevertheless, no solar *Injera* baking stove is available on the market yet. Further details of the economic analysis presented in this paper are published in Liyew et al. (2021).

The paper comprises two different studies: a survey on energy consumption in private households and a cost analysis of solar versus biomass and electric *Injera* baking stoves.

2. Household energy end-use consumption

A representative survey on the individual final energy end-use consumption in 721 private households was carried out in three cities in Ethiopia using questionnaires and measurements. Twenty-five households are excluded from the evaluations as some very important variables are missing. The study applies a bottom-up engineering method, using information from the survey and data collected by additional assessments and metering as implemented by Larsen and Nesbakken (2004). The average final energy consumption for each household is determined by summing up the final energy for cooking, baking, boiling, water heating, lighting, and other electric appliances for all energy sources. The share of energy consumption of the end-uses is calculated as the ratio of the average consumption of the respective end-uses to the total average consumption. The summary statistics of the survey data are shown in Tab. 1.

Dependent Variable	Min.	Max.	Mean	Std. Dev.
Energy for Injera Baking (kWh/a)	0	27,729	3,264	2,768
Energy for Wot Cooking (kWh/a)	1,807	13,459	3,810	1,633
Energy for Tea/Coffee Boiling (kWh/a)	0	4,891	971	556
Energy for Lighting (kWh/a)	0	3,285	162	225
Energy for TV & DVD player (kWh/a)	0	461	171	96
Energy for Water Heating (kWh/a)	0	143	14	40
Energy for Bread Baking (kWh/a)	0	548	39	141
Energy for Other HH electric appliances (kWh/a)*	0	818	360	394
Total final energy consumption (kWh/a)	2,730	33,307	8,792	3,410

Tab. 1: Summary statistics of the energy survey data (696 households). Data are presented as final energy.

*Other HH electric appliances include electricity for refrigerators, blenders, and washing machines.

The daily solid biomass fuel and electricity consumption was measured and a conversion factor of 19.45 MJ/kg for the biomass and one for the electricity consumption was applied. The survey yields a mean final energy consumption of about 8.8 MWh/a per household and the average family size is 4.6 ± 1.89 . It reveals that more than half of the household energy consumption is spent on cooking (Wot + tea/coffee boiling) and additionally 37% is spent on *Injera* baking, as shown in Fig. 1. The final energy consumption per capita yields 1.76 MWh/a. This is quite high compared to the per capita final energy consumption in developed countries considering no space heating/cooling requirement in Ethiopia. This is mainly because of the smaller ratio of useful to final energy for biomass, which is the dominant energy source in Ethiopia.

The household energy end-use analysis shows that almost the entire final energy consumption is suitable for the use of solar heat using concentrating solar collectors. Fig. 2 shows an overview of the end-uses identified and their suitability for the integration of solar heat, as they all are low and/or medium-temperature heating processes. The end-use temperature levels were determined in other studies (Mekonnen et al., 2020; Tesfay et al., 2014).



3. Injera baking stoves

A plate temperature ranging between about 135 - 220 °C is needed for *Injera* baking. Inefficient three-stone open fire biomass stoves with a conversion efficiency of less than 10 %, based on final energy, are still the most common

stoves used in rural Ethiopia. The thermal efficiency of the improved *Mirt* stove, shown in Fig. 3, ranges from 25–35 %. Electric *Injera* baking stoves, shown in Fig. 4a, are another competing and widespread baking technology. The rated power of an electric Injera stove is within the 3.7 - 4 kW range, with an efficiency of 40 - 50 % (Hailu et al., 2017). However, Jones et al. (2017) reveal that efficiency increment to about 30 % points can be achieved with improvements on the clay plate.

Concentrating solar collectors are suited for providing higher heating power per aperture area. This makes them suitable for *Injera* baking. In this study, the steam-based concentrating solar *Injera* stove, shown in Fig. 4b, is selected for economic evaluation as it is suitable for indoor cooking. It also allows cooking without in-between defocusing while pouring the dough on the plate. Nevertheless, it has a rather simple design and low costs, as it is designed without storage. It works as an indirect solar cooking system where water (steam) circulates. Using water as a working fluid enhances the thermal performance of the system due to its high specific heat capacity and high density. The system uses the natural fluid circulation principle with a boiling process at the receiver and condensation at the stove.



Fig. 3: Mirt improved biomass stove (Adem and Ambie, 2017)



Fig. 4: a) Electric Injera baking stove (Hailu et al., 2017) b) Block diagram of Steam-based concentrating solar Injera baking stove (Tesfay et al., 2014)

4. Levelized costs of heat for Injera baking

The levelized cost of energy (LCoE) is the discounted costs associated with a technical solution over its lifetime divided by the discounted energy produced, consumed, or saved (Louvet et al., 2019). The LCoE refers to the useful energy as well as the final energy for the stoves, i.e. the biomass and the electric energy. The average discounted price of final energy is also calculated for 20 years of investigation and compared with the LCoE. Different sizes of baking stoves influence the LCOE, however, to simplify the evaluations the calculations are based on the energy consumption of average family size of five members in Ethiopia. Furthermore, a 100% solar fraction is assumed as Ethiopia receives adequate sunshine hours due to its proximity to the equator.

The economic analysis of the solar *Injera* baking stove is performed by taking the *Mirt* stove as well as an electric stove as reference technologies to evaluate the LCoE. The costs accounted for are the initial investment, maintenance cost, salvage values, and the fuel expenditure of the individual technologies. The analysis is computed by considering the initial investment capital for all three technology options financed by a loan fund. The total investment cost of

the solar baking device is estimated as the sum of the market prices of the solar dish (including fluid loop), miscellaneous components, and the manufacturing cost because such kind of stove is not available on the market yet. As operating costs, local biomass and electricity prices with proper correction for market inflation rates are regarded. Both export and domestic electricity prices are considered for the economic analysis while substituting the electric stove with the solar *Injera* stove. The important considerations for the levelized cost of heat analysis are summarized in Tab. 2. The levelized cost of heat is calculated according to eq. (1).

$$LCoE = \frac{I_0 + \sum_{t=1}^{T} \frac{O_t + M_t}{(1+r)^t} - \frac{S_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}$$
(eq. 1)

Where the symbols in the equation are the initial investment (I_0), operation cost (O_t), maintenance cost (M_t), and salvage value (S_t), period of analysis (t), nominal discount rate (r), useful energy consumption (E_t), final biomass consumption (E_t), and final electricity consumption (E_t). The maintenance cost includes costs of the parts considered for replacement like the lifting cover made of mud for the *Mirt* stove; the switch and the resistor for the electric stove; and the baking pan assembly, the heating elements, the valves, and the pressure gauge for the solar *Injera* baking system. The replacement costs increase over time according to the market inflation rates.

Tab. 2: Summary of in	put data for the	levelized cost of	' heat analysis
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Parameter	Value
Biomass consumption of a household of five family members (the basis for <i>Mirt</i> stove)	5,372 kWh/a
Electricity consumption of a household of five family members (the basis for electric <i>Injera</i> stove)	486 kWh/a
Useful (heat) energy consumption of a household of five family members	72 kWh/a
The average number of <i>Injera</i> baked in a household of five family members	3,120 pieces/a
In flations under	12.5 % (in 2019/20 EFY*),
Inflation rate	12 % (in 2020/1 EFY and onwards)
Nominal discount rate	7 %
Export electricity price	14 US¢/kWh
	3.7 US¢/kWh (in 2019/20 EFY),
$\mathbf{D}_{\mathbf{r}}$	4.4 US¢/kWh (in 2020/1 EFY),
Domestic electricity price (2019-2023 plan)	5.7 US¢/kWh (in 2021/2 EFY),
	7.0 US¢/kWh (in 2022/3 EFY)
Biomass fuel price (the basis for Mirt stove)	2 US¢/kWh
The investment cost for the Mirt stove	15.3 US\$
The investment cost for an electric Injera stove	75.5 US\$
The investment cost for concentrating solar Injera stove	399 US\$
Period of analysis	20 years

*EFY=Ethiopian Fiscal Year

The levelized cost of useful heat, $LCoE_{useful}$, is evaluated based on the heat transferred from the baking plate to the *Injera*. Tab. 3 shows that in this case study $LCoE_{useful}$ for baking with the solar device is 1.76 \$ per kWh. This cost is nearly 60 % lower than the $LCoE_{useful}$ for baking with the *Mirt* stove, and about 52 % lower than baking with an electric stove when taking into account export electricity prices. When domestic electricity prices are regarded, the overall cost for solar baking is about the same as for baking with electricity. The levelized costs of energy differ mainly due to the different fuel costs, large inflation rates of more than 12 %, and different efficiencies of the stoves. The latter results in a distinctively higher biomass final energy consumption than electricity consumption.

The levelized cost of a kWh of biomass, $LCoE_{final}$, that is saved when a *Mirt* stove is replaced by the selected solar stove is 0.04 \$/kWh. Similarly, the cost of a kWh of saved electricity when an electric *Injera* stove is replaced by the selected solar *Injera* stove is 0.26 \$/kWh. Substituting *Mirt* stove by solar stove provides less costly heat when considering the substituted biomass energy. The substitution brings a price reduction of about one-third of the average discounted price of biomass. The average discounted price of biomass over 20 years of analysis period is about 0.06

\$/kWh; whereas the average discounted price of electricity is 0.14 \$/kWh with the domestic price and 0.39 \$/kWh with the export price.

Technology description	LCoE (\$/kWh)
Mirt stove, cost per kWh useful heat	4.30
Electric Injera baking stove, cost per kWh useful heat*	3.70
Electric Injera baking stove, cost per kWh useful heat**	1.90
Solar Injera baking device, cost per kWh useful heat	1.80
Solar Injera baking device, cost per kWh saved biomass	0.04
Solar Injera baking device, cost per kWh saved electricity	0.26
	•. •

Tab. 3: Levelized cost of energy (LCoE) referred to useful and saved final energy

*with export electricity prices **with domestic electricity prices

5. Conclusion

The survey of nearly 700 urban Ethiopian households reveals a mean annual final energy consumption of about 8.8 MWh/household. Of which, about 55 % of the total final energy consumption is spent on cooking and boiling, about 37 % for baking, and about 8.5 % for other household applications including lighting. The end-use analysis of the households shows that currently, almost all end-uses are suitable for the use of solar heat using concentrating solar collectors.

The economic case study presented in this paper reveals that *Injera* baking with the investigated indoor solar baking device without storage is significantly less expensive for the considered reference conditions than baking with common baking technologies when regarding the entire life span of the solar device. According to the evaluations, the LCoE_{useful} for the *Mirt* stove and an electric baking stove (considering export prices) is more than twice as high as the LCoE_{useful} of the investigated concentrating solar baking device. Also, substituting *Mirt* biomass stove with concentrating solar Injera stove provides substantial cost reduction compared to the average discounted price of biomass within a 20-years analysis period.

6. Acknowledgments

The data collection was supported by a grant from Bahir Dar University. The authors sincerely acknowledge Bahir Dar University for funding the energy data survey. The authors would also like to acknowledge the EECBP Ethio-German Homegrown Ph.D. Scholarship Program for providing the scholarship for the first author.

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I-06. Disinfection, Decontamination, Separation of Industrial Process Water and Wastewater

Evaluation of solar still depending on air velocity conditions

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Abstract

In solar distillation, the production of distilled water is a function of efficient design involving evaporationcondensation processes under variable operating conditions, such as solar irradiance, temperature, wind speed and direction, and thermodynamic parameters characteristic of the solar still type. The experimental results of the effect of air velocity in different modifications made on the double shed of the solar still on the productivity of distilled water under controlled conditions are presented. The study was conducted in Temixco, Morelos, Mexico, at 18° 54' north latitude and 99° 13' west longitude, with an average daily solar irradiance of 750 W/m². It was observed that under average daily irradiation conditions of 5.1 kWh/m², the still, cooled with a wind speed of 5.5 m/s, can produce 0.76 l in the case of confinement, or 0.66 l in the case of non-confinement of ambient air.

Keywords: Double slope solar still, Natural and forced convection, Wind tunnel, Energy efficiency.

1. Introduction

One of the most significant problems humanity faces is the supply of drinking water. Water desalination is a crucial solution to provide safe water and meet the world's growing population (Bamasag et al., 2020). However, the most widely used technologies for desalinization are highly intensive in energy consumption, such as thermal energy (evaporation) and electricity (compression and reverse osmosis). The current energy situation demands saving and efficient energy use and sustainable development. A viable option is to use renewable energy through solar water distillation. Its basic principle is the greenhouse effect: the sun heats an air chamber through the transparent glass; at the bottom, we have standing water to distill (García Valladares et al., 2017). Depending on solar radiation and other factors: such as wind velocity (which cools the outer glass), a fraction of this water evaporates and condenses on the inside of the glass, which is inclined; this inclination is fundamental to prevent it from coming back. the condensed waterfalls into the tray that contains the water to be distilled, so that the drops fall on a channel that collects said condensate (Castillo Téllez and Pilatowsky-figueroa, 2013).

In the case of double slope solar stills (DSSS), the influence of the different parameters on productivity (l/day) has been theoretically and experimentally analyzed. In the case of the effect of air velocity, this is an essential parameter that has a significant influence on the production of distilled water, especially on the cooling of the glass cover (condensate surface). A fraction of this water is evaporated and condensed in the glass cover, which is inclined, so that the drops fall into a channel that collects said condensate, preventing them from falling back to the lower sheet in the condensation process brine (Castillo-Téllez et al., 2015).

In the case of double house solar stills (DSDC), the influence of the different parameters on productivity (1/day) has been theoretically and experimentally analyzed. In the case of the effect of air velocity, few theoretical and less experimental works have been developed, and the reported conclusions do not coincide, sometimes contradictory. In the solar still, the amount of condensed water depends on the velocity and temperature of the ambient air, which vary throughout its operation, making it difficult to quantify the influence of each of them, first with the condensation capacity and finally with the thermal efficiency. In addition, the climatic parameters (air velocity, ambient temperature, irradiance, and relative humidity) cannot be controlled; therefore, it is complicated to determine the distilled water that can be obtained. In the case of different ambient air velocities: specially to achieve a homogeneous distribution on the condensation surface of the still.

Among the authors who have analyzed this effect theoretically, a theoretical study was carried out that predicts the productivity of a DSDC under different climatic, design, and operational parameters, concluding that an increase in velocity from 1 to 3 m/s results in 8% higher productivity (Al-Hinai et al., 2002). Regarding the works where an

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opposite effect or little influence of the air velocity is obtained, the different parameters that affect single slope solar performance are still analyzed in a study. It is concluded that as wind speed increases, distilled water production gradually decreases and when a change of 1 to 9 m/s occurs, productivity decreases by 13% (Rubio-Cerda et al., 2002). In another study, a mathematical model validated by an experimental work for a DSCS is proposed, and it is concluded that the wind velocity has a negligible effect on the production of water when increasing the velocity from 0 to 9 m/s; this increases a 10% (Nafey et al., 2000). In conclusion, few theoretical and experimental works have been developed, and the reported conclusions do not coincide, sometimes contradictory. Therefore, in this work, all efforts were focused on analyzing the conditions that still affect the operation of double house solar and its relationship with the influence of ambient air.

2. Materials and Methods

2.1 Experimental prototype

Experimental equipment consists: of two DSSS, each containing a copper tray, is square in shape, 16 gauge (0.5 m x 0.5 m x 0.05 m) with a maximum volume of 12.5 l of water to be distilled, with matt black paint resistant to high temperatures, with a catchment area of 0.25 m^2 . Both transparent covers are made of glass (3 mm thick) with a 23° inclination. The sidewalls and the bottom were thermally insulated with polyurethane foam thickness of 0.10 m. The liquid level to be treated is kept constant (2.5 cm). The amount of distilled water is recorded continuously, with a precision scale.

In the part where the two glass covers (booth) are recharged on the tray, there are two aluminum channels to which a slight slope and a ¼ inch hole were machined, which are the collecting and transport means of condensate. In the central part of the DSDC, a container distributes the water to the stills, maintaining a constant level of brackish water to be treated. Each still has an independent condensate collector, where distilled water is continuously recorded. The still was built with an orifice on one side to feed the tray with a ¼ inch hose with the water distilled. At the base, another ½ inch hole was located, used to eliminate the brine.

Instrumentations. For the temperature records, type K thermocouples were used, and the data were acquired daily using a Campbell Data Logger. These thermocouples have a calibration curve provided by the manufacturer and do not require additional calibration. They are coupled to the selected data logger; it correlates with voltage and temperature through a program that integrates the manufacturer to the data acquisition system.

A Tor-Rey electronic scale, model L-EQ 5/10, was used to determine the distilled water produced, with an accuracy of 0.01 kg; in the graphics on the distilled water production, you can see the error bars for this accuracy mentioned.

For the distribution and control of air velocity, four scenarios were proposed, which allow finding a relationship between wind speed and the increase or decrease in productivity: 1) Natural convection, 2) Natural convection and with acrylic cover, 3) Forced convection, fans in series with a double slope, 4) Forced convection, fans in series and without a wind tunnel. Comparison of the productivity of these scenarios allowed correlating the influence of air velocity and temperature. Three fans of dimensions $119 \times 119 \times 38$ mm were used to achieve the necessary rates to simulate different climatic scenarios, with a nominal voltage of 48V.

Figure 1 shows the experimental device in its various studied settings.



Fig. 1: DSSS in operation: 1) Natural convection, 2) Natural convection with acrylic cover, 3) Forced convection, fans in serial and double slope, 4) Forced convection, fans in serial and without wind tunnel

Daily meteorological information was acquired: solar irradiance, ambient temperature, wind speed and direction, and relative humidity, continuously recorded at the Renewable Energy Institute (IER) in Temixco, Morelos, Mexico. Tables 1 and 2 show the accuracy and description values given by the manufacturers of the different sensors used in

this solarimetric station.

Sensor	Maximum error (manufacturer)
Solar radiation	$\pm 0.5 \text{ W/m}^2$
Ambient temperature	±0.4 °C
Relative humidity	±3%
Wind speed	±0.5 m/s
Wind direction	$\pm 5^{\circ}$

Tab. 1: Accuracy of the measuring instruments (given by the manufacturers)

Tab. 2: Characteristics and description of the measuring instruments provided by the manufacturers.

Variable	Descripción	Modelo	Calibración
Global irradiation	Pyranometer Eppley	PSP	Anual (IGF-UNAM) (K=7.68 Sensor Campbell
Ambient temperature	Sensor Campbell,	1000 ΩPRT, DIN	Bianual (manufacturer)
and RH	CS500	43760B	
Velocity and wind direction	Wind Sentry mod 03002-5 R.M. Young Company	03002-5	Biannual (manufacturer)

2.3 Experimental procedure

The brackish water distribution container is supplied during the night to ensure the water supply to each still for its operation during the day, keeping the level in each constant at 2 cm through the continuous level burette. The variations of the temperatures inside and outside of the still, brackish water, environment parameters, solar radiation, and the selected velocity inside the wind tunnel are recorded. The distilled water is measured by recording its weight on the precision mentioned above balance. The measurement cycles are taken at 8:00 p.m. each day; at the beginning, the average air velocity is set, and the variations of the different parameters are recorded using an automatic data acquisition system. The covers are cleaned beforehand to prevent some particles from the environment from settling down and reducing their transmittance. Discussion and results

Figures 2 show the behavior of the average weather conditions corresponding to the test period, as a typical example of what can be expected in the locality where the study was carried out. A maximum ambient temperature of 28 °C was observed, while the minimum value was approximated at 7:00 a.m. Concerning the solar irradiance, measurement time shows a peak at 1:00 p.m. with a magnitude of 732 W/m². Regarding the relative humidity, it can be seen that the maximum value is 50%, while during sunny hours, the average was 30%.



Fig. 2: Irradiance, ambient temperature and relative humidity recorded by the solar station

3.1 Natural convection still

To determine the effect of forced convection in the efficiency of a solar still, it was necessary to resolve the thermal performance of the still without the convection device. Figure 3 shows the temperatures obtained in the still with



natural convection and the distilled water obtained as a function of the energy received in the collector (kWh) during



It is observed that the temperature between the interior and exterior glass are practically the same, reaching a maximum of 58 °C. However, the absorber temperature reaches a maximum of 77 °C, while the water surface temperature reaches 69 °C. It can also be observed in the bar graph that the distilled water obtained during the five consecutive days that were taken as a reference concerning the energy received in the collector (irradiation per collector area by the factor 0.814 derived from the attenuation of the cover glass), to analyze the behavior of the still with natural convection and have a comparison with other proposals presented in this work. It is also inferred that for average irradiation of 4.97 kWh/m², it still has an average production of 0.74 l. The highest volume of distilled water obtained was 0.82 liters for irradiation of 5.5 kWh/m².

3.2 Natural convection still with acrylic cover

To analyze the effect of placing the acrylic cover in the still with natural convection, Figure 4 shows the temperature profile in the still and the water obtained 5 consecutive days of testing.



Fig. 4: Measured temperatures inside and outside of the Natural convection still with acrylic cover and the distilled water obtained (l) as a function of the solar energy received by the still (kWh).

It can be observed that a maximum temperature in the absorber of approximately 60° C is reached, with irradiation of 4.5 kWh/m².

The obtaining of distilled water drops considerably highest than in the others cases because the percentage of irradiance that reaches the absorber and heats the water is lower due to the obstruction of this light beam due to the double cover: acrylic plus glass, both with a thickness of 3 mm. The correction factor due to the attenuation of the glass cover plus the acrylic cover is 0.66. Therefore, it is concluded that having a double cover lowers the still's performance by approximately 34%. The highest volume of distilled water obtained was 0.48 liters for solar energy received in the collector of 0.78 kWh, corresponding to a solar resource of 4.7 kWh/m².

3.3 Forced convection still with fans in serial and double slope

To increase the convection phenomenon on the DSSS glass slope, a 3.0 mm thick acrylic sheet with a visible optical transmission of 80.7% was placed over the covers to create a "wind tunnel." Three fans were placed in series in such a way that sufficient care was taken that the speed of the air injected by the fans was uniform over the entire roof surface and at different average wind speeds: 2.5, 3.5, and 5.5 m/s. The results of obtaining distilled water with the previous conditions are shown in table 3.

Collecting data date	Wind speed (m/s)	Average irradiance recieved (kWh/m ²)	Solar energy received (kWh)	Distilled water obtained (l/day)
July 24	2.5	5.22	0.860	0.61
July 2	3.5	5.18	0.854	0.75
August 2	5.5	4.91	0.810	0.76
September 13	6.9	5.10	0.842	0.62

Table. 3:	Results of	the still	with forced	convection.

During the days in which the experiments were carried out, the solar resource measured in the meteorological station was 5.1 kWh/m²; the variation in obtaining distilled water will only be assigned to the forced convection produced by the increase in air velocity. Under these conditions, the absorber, water, and indoor air temperature decreased from 69 °C, 65 °C, and 63 °C to 50 °C, 49 °C, and 49 °C, respectively. In general, it was determined that as the air velocity over the outer cover increases, the convection phenomenon increases, decreasing the temperature of the glass cover from 51 °C (v = 2.5 m/s) until reaching a value equal to the ambient temperature (v = 5.5 m/s). In this interval, the distilled water obtained is increased due to an increase in the condensation rate; this has the consequence: obtaining of distilled water increases until reaching a maximum value, which is obtained when the temperature of the outer cover is almost equal to that of the environment, and from there, the production decreases derived from the fact that the glass cover is colder than the environment.

3.4 Forced convection still with fans in serial and without wind tunnel

Measurements were carried out with the implementation of forced convection but without the wind tunnel to compare the natural action of the wind on the solar still; the speed at which the fans worked under these conditions was 5.5 m/s because, at this velocity, the highest production of distilled water was obtained in the previous scenarios.

In this case, the distilled water obtained was 0.66 l with irradiation of 4.01 kWh/m^2 , while the solar energy received in the collector was 0.816 kWh. For forced convection with the same air velocity (5.5 m/s) and solar energy received in the collector with similar values (0.816 kWh in this case and 0.81 kWh in table 3), the water production is 13% less than the one obtained when the air is confined in the double cover (figure 5).



Fig. 5: Obtaining accumulated distilled water on forced convection still with fans in serial and without wind tunnel

In this case, the distilled water obtained was $0.66 \ 1$ with irradiation of $4.01 \ kWh/m^2$ (value measured in the meteorological station), while the solar energy (Es) received in the collector was $0.816 \ kWh$. To compare the values in table 3 for forced convection with the same air velocity (5.5 m/s) and solar energy received in the collector with similar values., the water production is 13% lower than obtained when the air is confined in the double slope.

In analyzing the efficiency of a solar still, geometric parameters and those related to the materials' properties are involved. In the case of the double slope solar stills, the influence of these parameters on efficiency and productivity has been analyzed theoretically and experimentally. The efficiency of the Still (n) is calculated with the following

expression (Cooper, 1973):

$$\eta = \frac{(V * hfg)}{(P_{prom}) * H * 3600)} ; \eta = \frac{(V * hfg)}{(I_{prom}) * h * 3600)}$$
(eq. 1)

In the previous expression:

- V, is the volume of distillate (measured in liters, taking into account that one liter of water has a mass of 1 kg),
- Hfg, is the latent heat of vaporization with units of J/kg, whose value was obtained taking into account the maximum temperature obtained in the water to be distilled,
- P, is the power of the solar radiation that falls on the absorber surface (given by the product of the average irradiance I of the day measured in W/m^2 with the surface S of the collector measured in m^2),
- H, time exposure in hours (sunshine hours).
- The PxHx3600 product is the solar energy captured by the absorber expressed in Joule.

Day	Velocity (m/s)	Es (kWh)	V (1)	Hfg (MJ/kg)	n (%)	Study case
02-ene	0.00	0.854	0.56	2.366	43.1	Natural convection, without double cover
09-ene	0.00	0.823	0.57	2.366	45.5	Natural convection, without double cover
09-jun	0.00	1.01	0.688	2.366	44.8	Natural convection, without double cover
09-jul	0.00	0.78	0.48	2.342	40.0	Natural convection with double cover
24-jul	2.50	0.86	0.61	2.354	46.4	Natural convection with double cover
02-jul	3.50	0.854	0.75	2.378	58.0	Natural convection with double cover
02-ago	5.50	0.81	0.76	2.39	62.3	Natural convection with double cover
06-feb	5.50	0.816	0.66	2.39	53.7	Forced convection without double cover
13-sep	6.90	0.842	0.62	2.39	48.9	Forced convection with double cover

Table 4. It shows the efficiency of the DSSS with Natural and Forced convection in the conditions of this analysis.

3.5 Conclusions

In the present experimental work, the results of the analysis of the convective effect of air velocity on obtaining distilled water in a double house solar distillation system were presented. The air velocity domain was established from 0 m/s to 6.9 m/s, observing that an airflow that increases the convection phenomenon on the glass cover increases the efficiency of the still. The results obtained show a correlation between the wind speed on the glass cover and the obtaining of distilled water. It was found that under the same climatic conditions, forced convection in the speed range of 2.5 m/s to 5.5 m/s helps to increase the amount of distilled water obtained and increases the efficiency of the still, obtaining a value maximum of 62.3%. Under conditions of average daily irradiation of 5.1 kWh/m², the DSSS with an area of 0.25 m², cooled with a wind velocity of 5.5 m/s, can produce 0.761 in the case of confinement, or 0.661 in the case of non-confinement.

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J-01. Medium- and High-temperature Thermal Storage

Boundary conditions and Natural temperature decay from experimental data analysis to on-design of a tank for CSP plant Part 1

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Abstract

Applying the real boundary conditions and the time differential in a thermal volume implies the possibility of modeling the heat transfer dynamically, in this case determining an inertial accumulation of thermal energy of any kind. Hence, the ability to control heat losses and know the temperature trend of a tank on the walls can provide an interesting and innovative tool to guide solutions regarding the design of a molten salts Thermal Energy Storage (TES). The paper objective is first to have solved equations during a natural decay of temperature, for extending the following parts the discharging phases to most efficient design solutions. From the data of the experimental campaigns conducted since 2004, a thermodynamic solution has been modelled based on lumped-circuit abstraction under a set of imposed assumptions in a novelty way. This has been analyzed through a molten salt tank at experimental concentration solar power plant of Research Centre ENEA in Rome. Specifically, this Part 1 presents the method in use, namely that of simulating in a new way the value of the initial energy of a system different from zero as a function of the variation of time starting from a classical formula of the heat transport equation and using a lumped-circuit abstraction that can be better suited to variations and to the impositions of the boundary conditions. As a result, this paper holds the evidence between another use of lumped-circuit abstraction with no-zero initial energy varying on time as best modelling of real boundary conditions and a matching with known fundamentals in transient conduction, at the first time. That has been observed in a numerous natural discharging phases according to analyzed data (Appendix A). The result contributes to a greater understanding of heat transport and therefore to better orient the design choice. Finally, it has recalled the ongoing further developments of such new full-bodied modelling because such model based on the real conditions in use has different results according to an abstract switch witch open/close circuits depending on the variation of a component in function (Fig. 3).

Keywords: Lumped-circuit, Thermodynamic, Solar energy, Tank-storage

1. Introduction

The analysis during the experimental campaigns at ENEA Casaccia since 2004, and the last two ones with programme SFERA III 2020-21, show that the trend of the internal temperatures of a thermocline can be studied from the external thermocouples, in accordance with the relative cataloguing of data. Even though heat losses don't seem to have any occurrences or consequences through the tanks along the energy production, those have a significant role in the trend of extraction at right temperature, especially for thermocline. As first step, the study holds how the heat losses in a tank affect the internal temperatures without simplifications but setting boundary conditions close to a matter of facts. Therefore, the settings start from the data of the experimental campaigns to a modelled solution based on lumped-circuit abstraction under a set of imposed assumptions. The final purpose by observing the natural decay of temperatures as well as the level of molten salts, and stored energy is to optimize further the design and Distributed Control System during the discharging phase. Trivially, two conditions can be summarily identified, those in the discharge phase of the accumulated energy and those of heat losses in the charging phase, in the absence of significant atmospheric conditions, ceteris paribus.

On the condition that the focus is about the discharging phase, the points where there are heat losses must be identified and quantified consistently with the tank geometry and shapes. The Fig. 1 exemplifies how has been identified the areas of tank where the energy is lost direct to free stream conditions as specified further. Similarly, this has be done for all the point of tank. Those points according to temperature trend explain some
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crossing over between the curves when they are going to be observed closer. Besides, the boundary conditions of the thermocline have generally been limited to adiabatic conditions and omission of the perimeter bands to the tank. As result, the mathematical model applied to the system in operation and not simulated one imply a mismatch between an existing internal convection and radial motions and the temperature demand, namely lowering ability to extract a right flow temperature and its operating performance. In other word, it is not pointless to study the heat flow from inside to outside in operating mode to promote improvement and orientation for new storage solutions.



Fig. 1 Identified heat loss points on the top of molten salt tank SA.1.01

As matter of fact according to historical data, each operating day at experimental plant in Rome was recorded with date, hour when activity took place, eventually comments and especially values set in operation since 2004. For instance, the Fig. 2 shows what happened along a day. Peculiarly, it is known, according to the Fig. 2, that CS.1.01 was ON at 11 o'clock as well when the pump inside the tank was ON at 14:45 and OFF at 15:00 because of air-heater obstruction. Accordingly, when, and how long the reached temperatures at several blocks were known as well as the percentage of required power. Indeed, the initial and final temperatures along a planned process were known. As a result of this, to talk about real boundary conditions means use of real procedure in progress and known value where no doubt can be arisen. Matching the data with occurred activities on the plan, has permitted to outline the temperature on the tank-skin with a different point of view. Hence, the heat losses have had another significance values regarding the inside tank and motion or not of molten salt volume inside. Of course, this paper is limited to find out a specific equation which can correctly represent the temperature trend without other important boundary conditions. For instance, the dashed simulated green line in Fig. 2 shows the perfect matching of initial temperature (first green circle on the left side of curve) and the final lowered temperature (second green circle on the right side of curve).

Finally, the fundamentals of heat and mass transfer in relation to the principles of electrostatics, and more generally for what concerns inductances, resistances and capacities intended also in AC for some configuration, has been used to aid the right modelling of equations. Although this sensitive part will be dealt in a depth subsequent work, it is worth mentioning the conditions of natural temperature decay correspond to electrostatics conditions. This is going to introduce in the present paper to explain the nature of logic for such

novel type of lumped circuit abstraction (see Fig. 3) being applied with time-dependent initial energy for heat transfer.

Naturally, such association between the forms of heat transport, both steady-state and thermal transients, are not new in the field, but here the logic finds a new application. On that account, the idea to develop such fullbodied method can also be achieved thanks to the available automation technology when the concept of having multi-switch conditions (see Fig. 3) are activated according to the existing boundary conditions.



Fig. 2 Typical day compared to Experimental Plant Log Record where components' switching on/off can observed accordingly. TIX-1-3NN are thermocouples on the tank-skin. TT-1-05N are thermocouples installed at 100 mm from the tankskin. LT-1-050 is the measured level of molten salt into the tank. The red dashed line ALAC1-01 is the electrical power supplied to the tank when switched on [Watt on the right y-axe]. The dashed green line named IP is the simulated one according to the boundary conditions defined between the two points (green circles). Left Y-axe are temperature while X-axe is time along the experimental day in 2008.

2. Method

Since previous papers (Garimella, Flueckiger, 2012; Chao Xu et al. 2012; Gaggioli et al., 2018), particularly Preliminary Design Study in 2010 (Turchi et al. 2010), about simulated charge and discharging conditions validated on experimental data (Pacheco, Showalter, Kolb, 2002), a perimeter band thickness near the thermocline walls showed an involved area by a convectional motion, also mentioned in Zavoico, 2001. Concerned and assumed the same form factor, this perimeter thickness can statistically be calculated:

$$t_{conv} = 0.05 * \emptyset_{i,tank} \iff \frac{H}{\emptyset_{i,tank} + 2t_0} = 1.0962$$
(eq.1)

The thermodynamic parameters of materials were found in the literature (Zavoico, 2001; Green, Perry, 2008; Bergman, Lavine, 2017) as function of temperature between 260 to 600°C and compared with the values of the technical data sheets of the products in use. The geometric values of the tank and its layers were respectively approximated as following:

- the thicknesses of the materials **t** in geometric averages.
- the linearized development of curves measured in AutoCAD® in rotation surfaces.
- the surfaces measured in AutoCAD® of the actual shapes in rotation volumes.

Since the heat loss of the curved surfaces of the tank is less than an angle of $\pm 30^{\circ}$ from the horizontal plane, they have been simplified into vertical and horizontal ones – considering the heat transport on this curved surface underlies an insignificant residual volume (EN ISO 6946: 2017) –. The actual comparison between real shape/volume and simplified one is approximately 0.1%. Practically, no simplification or rounding is

performed on the real quantities of the tank and its form factors, even though the simulated shape has been based on an equivalent cylinder.

The time periods, where this study is based on, cover observations during the years 2004, 2008, 2018 and the last two experimental campaigns of SFERA III 2020 and 2021 as summarized in Appendix A. The most of initial data come since 2004 which are fundamental because of beginning of experimental solar power plant at ENEA in Rome. All these experimental data, received and analysed, have been compared with operating values and log registration to estimate the boundary conditions accordingly. Therefore, from the observation of the data and the application of a simple natural regression of these, it was verified whether the value of a hypothetical coefficient was factual, and if it could have been expressed as dependent on physical parameters, not exclusively as a mathematical one. Therefore, as a first approximation, an average value was evaluated from the regressions obtainable with respect to the temperatures recorded by the thermocouples assuming that data named *b*:

$$b = \left(\prod_i b_i\right)^{1/i} \tag{eq.2}$$

This made it possible to compare a single value in relation to a single thermocouple and therefore trivially with respect to each coefficient. It was mathematically obtained that:

$$a = \frac{y_i}{e^{-b\tau_i}}; b = -\frac{\ln\left(\frac{y_i}{a}\right)}{x_i}$$
(eq.3)

The mathematical solution, according to the assumptions made in the introduction, must involve the physical one, that is:

$$b \propto f\left(\frac{h_c A}{\rho V c_p}\right) = f\left(\frac{h_c}{\rho c_p}\left(\frac{A}{V}\right)\right)$$
 (eq.4)

Where it is observed that the ratio (A/V) is a shape ratio and therefore dependent on the geometry of a tank, thermocline, or storage. The other factors are physical parameters of which the density and specific heat can be considered constant as first stage in the given known range of temperatures. Besides, the convection coefficient h_c varies according to the interface and the type of occurred convective motion, assumed there is no mass exchange between the layer interfaces at first stage of analysis. The physical parameters of reference are strictly dependent on the materials, and, on a preliminary basis, some simplifications have been chosen to take up to verify the truthfulness or the validity of the assumption at least. For instance, the interface with steel was posited as non-existent as the thermal conductivity of the material is very high, and it follows that the resistance is negligible, given that:

$$R_{steel} = \frac{t_{steel}}{\lambda_{steel}} \le 1.8 * 10^{-4} \left[W \,^{\circ}C^{-1} \right], per \,\Delta T > 260 \,^{\circ}C$$
(eq.5)

Other formulation for used materials are in Appendix B.

Concerning the method, it should be clarified that the accumulation of energy as a difference of the accumulation initially owned and that transferred, is a result of thermal transmission $Q_i - Q_u$, so:

$$Q_0 - hA\theta = mc_p \frac{d\theta}{d\tau} \tag{eq.6}$$

This expression is usually resolved by erasing the value of the double integral leading to the more well-known expression:

$$\theta = \theta_i e^{-b\tau}, \begin{cases} \theta = T - T_{\infty} \\ \theta_i = T_i - T_{\infty} \end{cases}$$
(eq.7)

Therefore, in the steady-state phase it is observed by data that:

$$\tau_t^{-1} = \frac{hA}{\rho V c_p} \propto b/T \tag{eq.8}$$

The problem then shifts to the search for the law of variation of the initial reference temperature as follow. Conversely, the observed initial peak heat loss in each case the supplied energy was suspended, either electrical boiler or solar trough of salt circulation, has also been studied in form of an impulse, but it is not included in this paper. Therefore, the initial temperature has been taken after this first peak phase, Fig. 4 peak area. Still concerning the method, the behaviour of the salts in the thawing phase due to the temperature natural decay were studied on a different tank during the SFERA III second experimental campaign, so-called Reslag. This tank has a scalable geometry according to (eq. 1) and it was fundamental for the verification and definition of transient temperature response of lumped capacitance for the thermal time constant.

As matter of fact, the possibility to relay on a natural trend of molten salt has led to associate each observable conditions around the tank with a lumped-circuit concept.

In accordance with picture Fig. 3, a multi-switch operates different electrical circuits settled with the action or reaction observed. Hence, Fig. 3 shows the electrical circuit associated to boundary conditions during the natural decay of temperature. The values of capacitor are the molten salt lumped thermal capacitance in Fig. 5, namely the initial cumulated energy at shown stage, while the resistances are convection layer heat loss towards stream like ullage and transient conduction towards solid materials like insulation of tank.



Fig. 3 Lumped-circuit model where each electric circuit corresponds toa group of boundary conditions according to the observed tank case or phase

3. Modelling equations

The novel full-bodied model and its development would require more than one paper according to conditions among most the condition summarized in (eq.16); therefore, equation modeling and their boundary conditions are as per the diagram in Fig. 3, postponing in the final outlook some conclusions and further improvements.

As mentioned in Section 2. Methods, the modelling of temperature decay equation starts from a general regression or so-called Newton's non-linear problem. The natural regression of a data cloud strongly depends on how close the initial condition is to have a convergence of the curve. Being more specific, given the temperatures \mathbf{y} recorded each time interval \mathbf{t} , the problem can be presented generically as follows (where \mathbf{x} -es are recorded temperatures):

$$x_{k+1} = x_k - \frac{g(x_k)}{g'(x_k)} \iff g(x_0) = 0 \implies \begin{cases} x_{0+1} = x_0 - \frac{g(x_0)}{g'(x_0)} = x_0 \\ x_{1+1} = x_1 - \frac{g(x_1)}{g'(x_1)} \\ \vdots \end{cases}$$
(eq.9)

If we extend the problem to multiple recorded temperatures, in presented tank means 3 thermocouples, it follows that the general expression can be written in vector form as (typical in-use Math notation):

$$x_{n+1} := x_n - \frac{S'(\tilde{x})}{S''(\tilde{x})} \iff \begin{cases} S'(\tilde{x_0}) = 0\\ \nabla S(\tilde{x}) = S'(\tilde{x})\\ \\ S''(\tilde{x}) = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 x_2} & \frac{\partial^2 f}{\partial x_1 x_3}\\ \frac{\partial^2 f}{\partial x_2 x_1} & \frac{\partial^2 f}{\partial x_2^2} & \frac{\partial^2 f}{\partial x_2 x_3}\\ \frac{\partial^2 f}{\partial x_3 x_1} & \frac{\partial^2 f}{\partial x_3 x_2} & \frac{\partial^2 f}{\partial x_3^2} \end{bmatrix}$$
(eq.10)

Trivially, the Hessian matrix, thus generically defined, is resolved in the following way, called \tilde{a}, \tilde{b} , the regression coefficients of the temperatures recorded in vector form:

$$f(\tilde{a}, \tilde{b}, \tau) = \tilde{a}e^{-\tilde{b}\tau}$$
(eq.11)
Given that:

$$\boldsymbol{S}(\tilde{a},\tilde{b}) = det \begin{bmatrix} S(\tilde{a})\\ S(\tilde{b}) \end{bmatrix} = \sum_{i=1}^{n} \left(\tilde{a}e^{-\tilde{b}\tau_{i}} - T_{i} \right)^{2}$$
(eq.12)

As first approximation, the concerned regression relationship can be considered valid for the temperatures that naturally decay according to the following general equation (eq.13) (Dark dots line in Fig. 4), so:

$$T = T_i e^{-b\tau} \tag{eq.13}$$

Consequently, eq.9 doesn't give any other change if an action or reaction occurs. As result of the investigation between the natural decay of tank temperatures and the thermal constant of time, it has been developed by complete solution of the differential equation (eq.14). Experimentally, it provides an excellent approximation of the decay of temperature under a set of imposed assumptions, Fig. 4 red line targeted IP.

$$Q_0 - hA\theta = mc_p \frac{d\theta}{d\tau}$$
(eq.14)



Fig. 4 The orange line shows TIX-1-321 thermocouple of thermocline skin tank along natural temperature decay. The red one is the simulated curve (IP in the chart), and the dark dots line is approximation according to natural regression.

As matter of fact, called Q_0 as the initial stored energy, and defined the thermodynamic parameters according

to exemplified lumped-circuit abstraction in Fig. 5, namely found the equivalent values of the reference electrical circuit, i.e., heat transfer coefficient assumed under the boundary conditions between the interfaces of the materials, and the initial accumulation of the capacitor, it can be written in a general manner by literature that:

$$-\frac{hA}{\rho V c_p} \int_0^\tau d\tau = \int_{\theta_i}^\theta \frac{d\theta}{\theta} - \frac{Q_0}{\rho V c_p} \int_0^\tau \int_{\theta_i}^\theta \frac{d\theta}{\theta} d\tau$$
(eq.15)

The eq.15 could have different solution according to how the initial stored energy varies, and whether an error function should have been applied – known in literature and applications with semi-infinite solid transient heat flow –. These involved mathematical conditions can be listed as below. Here, the paper holds shortly the solution according to the third one among the list in (eq.16).

$$\begin{array}{l} 1-Q_{0}=0 & \wedge erf(\eta_{a})=0 \\ 2-Q_{0}=const. \wedge erf(\eta_{a})=0 \\ \textbf{3}-\textbf{Q}_{0}:\textbf{Q}_{0}(\tau) & \wedge erf(\eta_{a})=0 \\ 4-Q_{0}:Q_{0}(\theta) & \wedge erf(\eta_{a})=0 \\ 5-Q_{0}=0 & \wedge erf(\eta_{a})\neq 0 \\ 6-Q_{0}=const. \wedge erf(\eta_{a})\neq 0 \\ 7-Q_{0}:Q_{0}(\tau) & \wedge erf(\eta_{a})\neq 0 \\ 9-Q_{0}:Q_{0}(\theta,\tau) & \wedge erf(\eta_{a})=0 \\ 10-Q_{0}:Q_{0}(\theta,\tau) & \wedge erf(\eta_{a})\neq 0 \end{array}$$

(eq.16)

Firstly, the analysis of initial temperature has been observed by the received data, and initial approximations of the differential calculus, named the initial temperature of thermocouple *TT* in the subscript, $T_{i,TT}$, can be trivially obtained as in eq.17, which within a temperature range [260°C,600°C] of molten salts, has a statistical tolerances that can be evaluated as in eq.18 (Please note that temperatures are highly dependent on the place of installation of the tank and the date referred to T_{∞}).

$$\theta_i = T_i - T_{\infty}$$
(eq.17)
$$T_{i,TT} = T_{max}(\pm 5^{\circ}\text{C}) + T_{\infty}(\pm 7^{\circ}\text{C})$$
(eq.18)



Fig. 5 Lumped-circuit abstraction under a set of imposed assumptions of tank at ENEA Casaccia Roma – Used in this modelling along experimental campaigns and based on data since 2004. The resistance in the pictures are equivalent one according to transient and materials in use (Appendix B).

The same initial temperature is also found trough modelling as a weighted average with respect to the level of molten salts, i.e., its volume in the cooling phase. In fact, it occurs that $T_{i,TT}$ is equal to:

$$T_{i,TT} = T_0(\tau, H_{lms}) + T_{\infty}$$
(eq.19)

Where $T_0(\tau, H_{lms})$ is the initial temperature weighted as a function of the time intervals in which the salt level and the volume of the salts vary, therefore equal to:

$$T_{0}(\tau, H_{lms}) = \sum \left(\left(\prod_{i} \frac{T_{TT,max,i} + T_{TT,min,i}}{2} \frac{V_{ms,i}}{V_{T}} \right)^{\frac{1}{i}} + \left(\prod_{j} \frac{T_{TT,max,j} + T_{TT,min,j}}{2} \frac{V_{ull,j}}{V_{T}} \right)^{\frac{1}{j}} \right)_{,k} \frac{\Delta \tau_{k}}{\Delta \tau} \qquad (eq.20)$$

Thus, obtaining an expression entirely dependent on physical and geometric parameters. Furthermore, the skintemperature could be intended as quasi-uniform, but the proportion between the molten salt mass and ullage becomes fundamental to determine this temperature, especially during variations of molten salt level. The existence of outer thermocouples installed on tank-skin aid to find a consistent relationship between inner crossover curves and out crossover curves. This has been explained by Fig. 6, in which the three thermocouples should show the same temperature theoretically, but indeed they behave differently when crossover. In other words, if there is a greater heat loss on a point of the tank and therefore is cooling faster, it is truism consider that the heat flow on an ideal horizontal section is directed towards this area. This calls into question the stability of the temperature of the mass of salts extracted ideally on the horizontal section from a certainly fixed point corresponding to the pump, for instance. Hence, the referred equation (eq.14) according to third boundary conditions in (eq.16) could be written in the form:

$$\frac{d\theta}{d\tau} - \frac{hA}{mc_p}\theta = \frac{1}{mc_p}Q_0 \tag{eq.21}$$

This is a first order linear differential equation of type:

$$\frac{d\theta}{d\tau} + f\theta = ag \tag{eq.22}$$

Where the initial accumulated energy is imposed dependent on time $Q_0(\tau) = g(=Q_{0,\tau})$, and the coefficients f and a could be taken as constant in the range of natural temperature decay. So, the solution is known as:

$$\theta = \frac{\int e^{-f\tau} Q_{0,\tau} d\tau + \kappa_0}{e^{-f\tau}} = \frac{\int e^{-f} Q_{0,\tau} d\tau + \theta_i e^{-2bf\tau}}{e^{-f\tau}}$$
(eq.23)

The value κ_0 is found out by imposing that this solution could be equal to the condition $Q_0(\tau) = 0$, i.e., not time dependent (Condition 1 in eq.16). As result, the problem became how to find the function $Q_{0,\tau}$. The solution of the equation for temperature decay of molten salt has been figured out by observing that (eq.23) can trivially be written as:

$$\theta_I + \theta_{II} = \frac{\int e^{-f} \ \varrho_{0,\tau} d\tau}{e^{-f\tau}} + \theta_i e^{-b\tau}$$
(eq.24)

Considering that an error function is set to zero, $erf(\eta_a) = 0$, because it is not the case here, consistently with the sum addenda:

$$\theta_I = \frac{\int e^{-f\tau} \varrho_{0,\tau} d\tau}{e^{-f\tau}} \tag{eq.25}$$

Differentiating both members, the result $(1 + f)/(-f) \cong 1$, so:

$$d\theta_I = e^{-f\tau} Q_{0\tau} d\tau \tag{eq.26}$$

This could be written as:

$$c(=Q_{0,\tau})\frac{d\tau}{\tau} = \frac{d\theta_I}{\tau e^{-f\tau}}$$
(eq.27)



Fig. 6 Blue hatch and dashed lines point the discharging phase, i.e. TIX319>TIX321>TIX320, while red hatch and dashed lines point the charging phase, i.e., TIX319>TIX320>TIX321. The shapes are weightings between the 3external and internal temperatures by thermocouples at different angles

The second member are temperatures over time, therefore can be re-written compactly:

$$c = \frac{\int \frac{d\theta^*}{\theta^*}}{\int \frac{d\tau}{\tau}}$$
(eq.28)

By integrating and applying the properties of the logarithms of the base change, the result is:

$$c = \frac{\ln\left(\theta^{*}(\tau)\right)}{\ln\left(\tau\right)} \Rightarrow c = \log_{\tau} \theta^{*} \tag{eq.29}$$

To conclude, the searched equation is:

$$\theta = \theta_i e^{-b\tau} + \tau^c \tag{eq.30}$$

This equation can simulate the natural temperature decay accurately - Fig. 4 targeted IP -.

Finally, this new application with lumped-capacitance circuit in Fig. 5 and the third conditions in eq.16 leads to solution in (eq.30). The value sought with respect to b as a function of the time constant τ_t given the probability of error based on a standard deviation σ has been omitted to focus on the presented result in Fig. 4 which is similar to any other thermocouple at the same conditions. This is extremely interesting because of able to simulate what happen accurately around and inside the tank. However, during the experimental phase, the temperatures θ are measured, and correspond to the trend from the tank-storage setpoint to the minimum temperature set (300°C in Fig. 4). Conversely, during the design phase the temperature design will be the compensation of average outdoor temperature in free stream condition that allows to find the coefficient b,

namely it depends on the time constant given a scheme in Fig. 5 with significant advantages concerning ondesign performing solutions. To be consistent the search of this value has been postponed to an ongoing further project-work being strictly connected to the chosen both boundary conditions and the lumped circuit.

4. Conclusion and outlook

From the experimental data to the modelling and improving of a governing equation, which uses an initial thermal stored energy varying on time, it can be drawn an advantage in terms of obtained more understanding of heat loss, but also, the lowering temperatures of the salts as a function of internal physical parameters. This investigative analysis allows to simulate accurately the trend of the temperatures inside the tank volume in the operation conditions concerning point 3 at (eq.16), i.e., natural temperature decay, which will have some relationship with discharging ones. Indeed, the discharging operation is essential for the thermal energy demand. Hence, to analyze how the molten salt behaves in several boundary conditions according to the applied lumped capacitance concept in dynamic mode, grant the right temperature to the power block. Closely related to the results of this paper, the heat transfer equation can be solved in a non-trivial way, not neglecting the fact that the initial energy of a system is not zero, and that its temperature decays in relation to time, where no other specific condition occurs. The novelty is limited to the presented conditions along the paper. However, proceeding is essential to build up a correct aid for sizing and make right geometry for storages, or any tank prone to be a thermal storage, especially thermocline one. Therefore, further improvement and an outlook of reliable developments, which are already ongoing, are worth to be mentioned:

- completing all assumptions as starting point for evidence
- discretization and simulation of model
- validation based on experimental data
- on-design tank modelling
- off-design tank modelling

Acknowledgement

We thank ENEA for the support of its scientific and technical staff provided during the access SURPF2001170003A to PCS facility. The access SURPF2001170003A was arranged in the frame of H2020 SFERA-III project activities – European Union's Horizon 2020 G.A. n. 823802 –.

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Appendix A

Tab. 1 ENEA experimental data, received and analyzed, in accordance with the PCS operating conditions ongoing recorded – Log registration in column ENEA LOG-RECORDS Yes=1 means existence and studied data accordingly, No=0 (only data) means it was not possible to get the log registration in that day or period or day for several reasons.

Prg.	Date in: 2004 2005 2008	ENEA LOG- RECORDS Yes=1 No=0 (only data)	Prg.	Date in: 2008 2018 2020-2021 SFERA III	ENEA LOG- RECORDS Yes=1 No=0 (only data)
1	02.04.2004	1	23	01.04.2008	1
2	05.04 to 08.04.2004	1	24	09.07.2008	1
3	09.04 to 12.04.2004	0	25	17.09.2008	1
4	13.04 to 16.04.2004	1	26	25.09.2008	1
5	17.04 to 19.04.2004	0	27	01.10.2008	1
6	20.04 to 21.04.2004	1	28	08.10.2008	1
7	26.04 to 30.04.2004	1	29	16.12.2008	1
8	01.05 to 02.05.2004	0	30	22.12.2008	1
9	07.05.2004	1	31	27.08 to 30.08.2018	0
10	14.05.2004	1	32	05.09 to 06.09.2018	0
11	17.05.2004	0	33	17.09 to 18.09.2018	0
12	18.05.2004	1	34	18.10 to 22.10.2020	0
13	19.05.2004	0	35	02.02 to 04.02.2021	0
14	20.05 to 22.05.2004	1	36	20.07 to 24.08.2021	0
15	25.06 to 23.08.2004	0	Mis	ss a period test for power los	s along CSP
16	24.08 to 27.08.2004	1		because of service	
17	28.08 to 29.08.2004	0			
18	30.08 to 31.08.2004	1			
19	01.09 to 17.09.2004	1			
20	14.01 to 18.01.2005	0			
21	28.02.2008	1			
22	12.03.2008	1			

Appendix B

Material	Thermal physical property	Equation
Air, <i>air = ull</i>	Thermal conductivity, k_{air}	$k_{air} = 0,224 + (8,02)10^{-4} T - (3,28)10^{-7} T^{2} [W m^{-1} \circ C^{-1}]$
	Density, $ ho_{air}$	$\rho_{air} = 2,8953 + 0,26733 T + 132,45 T^{2} + 0,27341 T^{3}[K] [kg m^{-3}]$
	Specific heat, <i>C_{p,air}</i>	$c_{p,air} = 0,10 + (1,40)10^{-4} T + (1,01)10^{-7} T^{2} - (5,69) 10^{-11} T^{3} [J kg^{-1} C^{-1}]$
	Viscosity, μ_{air}	$\mu_{air} = [0,1726 + (4,52)10^{-4} T - (1,937)10^{-7} T^2 + (4,185)10^{-11} T^3] 10^{-4} [°C] [kg m^{-1}s^{-1}]$
Stone mineral wool, <i>iso</i>	Thermal conductivity, k_{iso}	$k_{iso} = 0,106 \ [W \ m^{-1} \ K^{-1}]$
	Density, $ ho_{iso}$	$ \rho_{iso} = 100[kg \ m^{-3}] $
	Specific heat, <i>Cp,iso</i>	$c_{p,iso} = 1030 \left[J \ kg^{-1}K^{-1} \right]$
Molten salt, ms	Thermal conductivity, k_{ms}	$k_{ms} = 0,443 + 1,9 \times 10^{-4} T [W m^{-1} °C^{-1}]$
	Density, $ ho_{ms}$	$\rho_{ms} = 2090 - 0,636 T[^{\circ}C] [kg m^{-3}]$
	Specific heat, <i>Cp,ms</i>	$c_{p,ms} = 1443 - 0,172 T [J kg^{-1} C^{-1}]$
	Viscosity, μ_{ms}	$ \mu_{ms} = [22,714 - 0,12 T + 2,281 \times 10^{-4} T^2 - 1,474 \times 10^{-7} T^3] \times 10^{-3} [°C] $ $ [kg \ m^{-1}s^{-1}] $
Steel, <i>stl</i>	Thermal conductivity, k_{stl}	$k_{ms} = 60 \ [W \ m^{-1} \ K^{-1}]$
	Density, $ ho_{ms}$	$ \rho_{stl} = 8000[kg \ m^{-3}] $
	Specific heat, <i>Cp,stl</i>	$c_{p,stl} = 480 \ [J \ kg^{-1}K^{-1}]$
Aluminum, alu	Hemispherical emissivity	$\varepsilon = 0,1 [-]$

Tab. 2 Thermal-physical properties and constitutive correlation to the temperature

Definition of key performance indicators (KPIs) to evaluate innovative storage systems in concentrating solar power (CSP) plants

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Abstract

The increasing penetration of renewable energies into the energy system is leading to significant development and deployment of generation plants based on the use of solar energy. On large scale, concentrating solar power (CSP) plants is the starring technology. In those systems, thermal energy storage (TES) is an essential component that allows both providing dispatchability and increasing power production thus improving the plant efficiency and reducing both its size and cost. Current storage technologies are mainly based on solar salts (molten salts) and saturated steam, their main drawback being their operating temperatures. Therefore, the current challenge is to develop innovative solutions that allow CSP plants to work at higher temperatures to increase their efficiency. In order to allow the comparison of new TES concepts, the definition of proper key performance indicators (KPIs) helps to better identify the best storage solutions. This paper reports a preliminary selection of KPIs suitable for TES systems and their validation against the commercially available two-tanks molten salts storage concept for a 100 MW net capacity CSP tower plant to allow the comparison with innovative solutions. The results of this study can be used as a basis for comparison of TES technologies with the available ones, as well as to set the target for the research and development of future storage solutions.

Keywords: concentrating solar power (CSP) plant; solar thermal electricity; thermal energy storage (TES); key performance indicators (KPIs);

1. Introduction

Solar thermal electricity production represents one of the most effective technology that allows the exploitation of renewable energy sources with the potential to reduce the dependency from fossil fuel, thus decreasing carbon emissions into the atmosphere. According to the European Solar Thermal Electricity Associations (ESTELA, 2021), concentrating solar power (CSP) plants will have a substantial development and deployment before 2050. This growth can be attributed both to cost reduction and support of policies that aim to increase the share of renewables (McPherson et al., 2020). In order to offer electricity dispatchability and to adapt the electricity power production to the demand curve, thermal energy storage is an essential component of CSP plants (González-Roubaud et al., 2017). Furthermore, as reported by Gasa et al. (2021), the use thermal energy storage has a strong positive effect on the environmental impact during the life-cycle of a CSP plant. Current commercial thermal energy storage systems in CSP plants are steam accumulators and molten salts. Steam accumulators had a rapid deployment in the last years and they are used for very short storage periods (i.e. 5 hours). However, this technology is only suitable for small-scale plants due to their high pressure of saturated water used as storage medium, and their cost for high storage capacity (Palacios et al., 2020). On the other hand, molten salts represent the most used technology for CSP plants mainly in two-tank configuration. This storage technology can be used for longer periods (i.e., 8 h to 16 h), and it is characterized by high energy density and high cycling stability and lifetime. However, the main limitation of molten salts is their operating temperature (up to 565 °C for direct TES systems) because higher temperatures would cause their decomposition. Generally, the need to decrease costs and overcome the actual limitations of the current energy storage technologies is bringing a lot of research on new innovative storage concepts and systems. Those technologies include the use of phase change materials (Prieto

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and Cabeza, 2019), thermochemical energy storage (Prieto et al., 2016), and sensible material such as concrete (Boquera et al., 2021) and liquid metals (Lorenzin and Abanades, 2016). Due to the difference between the different storage systems that bring their own advantages and limitations, the comparison between different thermal energy storage concepts is difficult and, consequently, the identification of an optimal storage solution for a specific CSP plant configuration is a challenging task.

In this case, the identification of suitable key performance indicators (KPIs) is important to allow the comparison between thermal energy storage systems and to set the target for the potential development of innovative storage solutions to overcome the limitation of commercial storage technologies. The main aim of this study is to define simple KPIs able to carry out a preliminary comparison between different thermal energy storage solutions. Furthermore, the KPIs analyzed in this study were quantitatively evaluated for a commercial molten salts storage system. The results reported in this study can be used as baseline in future studies to compare actual technologies with other innovative thermal energy storage systems. Future research would include the use of such indicators in alternative TES technologies, such as concrete, thermochemical, or PCM storage allowing their comparison for the optimization of CSP plants.

2. Methodology and KPIs definition

A KPI can be defined as a parameter to evaluate the progress or the achievement of an operational strategic goal. The choice of the correct KPI is important to identify and understand the parameters that are relevant in a specific technology and allow a comparison amongst the different ones. Indeed, the most suitable technology for a general application can vary according to its boundary conditions. A general classification of existing KPIs can be:

- Technical performance indicators
- Economic performance indicators
- Environmental performance indicators

In the field of thermal energy storage, there is no clear definition and agreement about the KPIs to be used to compare different storage solutions. This is mainly due to their large range of applications and the low level of penetration of some of TES technologies. In order to select the most proper KPIs, different methods were developed in the literature. A first attempt to collect KPIs for TES in CSP plant was published by Cabeza et al. (2015) that listed and quantitatively compared different performance indicators. Palomba and Frazzica (2019) developed a methodology for KPI definition and proposed a set of KPIs to be used to compare different TES. However, analyzing the literature, the relevant characteristics that should be considered in TES systems can be identified. Important features that a KPIs should have are simplicity, clear and unique definition, and meaningfulness. Furthermore, a proper KPI should consider the requirements of both system (in this case CSP plant) and stakeholders. In this paper, a preliminary selection of KPIs was done by the authors based on the literature available and the requirements of stakeholders involved in this study related to the installation and maintenance of CSP plants. In order to select the KPIs, the first issue is to decide the boundaries of the system to be considered. Indeed, indicators suitable to characterize a thermal energy storage integrated into a CSP plant can be calculated at different levels, starting from system level (all CSP plant), sub-system level (tower system and the storage system until the heat exchanger of the power block), component level (only thermal energy storage) until KPIs at material level (TES medium). KPIs selected at different levels could be interesting to evaluate different aspect of TES. KPIs at thermal energy storage level are useful to compare the different storage technologies, but it is important to consider also the effect of the integration of TES into the CSP plant. Indeed, as demonstrated by Gasa et al. (2021), the integration of thermal energy storage highly affects the performance of the whole CSP plant such electric energy consumption that affects directly the CO₂ emissions,. In this paper, some relevant KPIs that can be applied to most of the storage technologies were selected at thermal energy storage level and reported as follows (Cabeza et al., 2015; Del Pero et al., 2018; Gasia et al., 2017; Palomba and Frazzica, 2019):

• KPI 1 – Nominal capacity [MWh_{th}]: amount of energy that can be stored in the storage at nominal conditions. Capacity is measured as the total net energy used to charge the storage system from 0% to 100% at nominal temperature and it depends on the storage process, the storage medium, and the size of the system.

- KPI 2 Charge and discharge time [in h]: duration of the charge and discharge phase of the thermal energy storage system. It can be calculated as the ratio between the energy delivered by (or supplied to) the thermal energy storage [MWh] and the nominal power discharged by the storage [MW] fixed in the characteristics plate.
- KPI 3 Operating temperature range [°C]: it is the temperature range in which the storage material can operate. This is important for sensible TES. For latent heat TES, since the thermal energy is stored and released at almost constant temperature, the phase change temperature will be the key parameter.
- KPI 4 Efficiency [%]: ratio of energy delivered during discharge between the energy stored during the charge. Therefore, it can be calculated as:

$$\eta = \frac{|Q_{discharge}|}{|Q_{charge}|}$$
(eq. 1)

where $Q_{discharge}$ is the heat delivered from the TES during the discharge [MWh] and Q_{charge} is the heat absorbed by the TES during the charge [MWh]. This performance indicator is affected by the energy losses of the system and the heat transfer efficiencies of the charging and discharging processes, respectively.

- KPI 5 Cost [in \$/kW or \$/kWh]: cost referred to the power or capacity of the storage system; it can be referred as thermal or electric cost.
- KPI 6 Environmental impact [kgCO₂eq./MW_{th}]: In this case, this performance indicator is only related to the production and the disposal of energy storage system. To evaluate the impact throughout all the life-cycle of the TES, the energy consumed during the operational stage (electricity consumption from the grid) has to be known.

Although, other performance indicators can be used to compare different thermal energy storage technology, these six basic KPIs can be considered useful for a preliminary evaluation of different thermal energy storage systems. Nevertheless, other than the preliminary KPIs reported above, additional key performance indicators can be defined for future comparison of energy storage solutions in CSP applications, considering the requirements of the new key role of TES such as:

- Technology Readiness Level (TRL): it indicates the maturity of a given technology. The TRL spans over nine levels. This KPI is especially relevant when comparing solutions under different stages of development with commercial solutions.
- Days of storage at nominal conditions [day] for seasonal storage application.
- Response time [minutes]: it indicates time of the TES to change its output level from rest to nominal power.

Furthermore, KPIs at system and material level can be considered in future studies to have a complete comparison between different storage technologies integrated to CSP plants.

3. Case study validation

In this study, the identified six KPIs are calculated and validated against a two tanks direct system used in a commercial CSP plant shown in Fig. 1. The plant (solar power tower (SPT)) consists of a solar field, a receiver system (solar tower), a thermal energy storage system, and finally a power block to generate electric output. The main characteristics of the plant are:

- Net capacity: 110 MW
- Receiver power level: 690 MW
- HTF mass: 46,000 metric ton
- TES storage capacity: 4,695 MWh_{th}
- Annual net electricity fed to the grid: 776.24 GWhel

The thermal energy storage system consists of the following elements: storage medium (molten salt), hot and cold storage tanks, and molten salt circulation pumps. In this plant, the heat transfer fluid (HTF) and the storage media is the same material. The solar salt used as storage media is a mixture of 60wt.% NaNO₃ and 40wt.% KNO₃, with a melting point of 220 °C, maximum operation temperature of 565 °C, specific heat of 1,495 J/kg·°C, density of 1,899 kg/m³ (at 300°C), and a cost of 1.30 \$/kg.



Fig. 1. CSP plant configuration used in this study to calculate the KPIs (Gasa et al., 2021)

In this system, heliostats concentrate sunrays by reflecting them to a tubular-type receiver that transfers the energy flux to the HTF. During this step, the salts are heated up to 565 °C and pumped into the thermal energy storage tank (hot tank). The hot salt can then be stored or directly used to produce steam, which is used in the power block to generate electricity through a turbine. The cooled salt (around 290 °C) is then returned to a second thermal energy storage (cold tank) ready to be heated up again when the solar field is available. In this plant, thermal energy storage act as a buffer for the molten salt steam generator to supply energy during periods of no solar radiation such as night or cloudy days. However, TES can be implemented in CSP plants using different strategies: intermediate load configuration, delayed intermediate load configuration, peak load configuration, and baseload configuration ([IEA] - International Energy Agency, 2010). Thermal energy storage tanks in CSP plants need special design features to limit mechanical stress resulting from the thermal effects due to their high temperature operation. Cold storage tanks are commonly fabricated with carbon steel (ASTM A-516 Gr.70), while hot storage tanks are fabricated with stainless steel (ASTM A-347H or ASTM A-321H) (Gasa et al., 2021). The thermal energy storage of the CSP plant used to validate the KPIs proposed in this study had a storage capacity in molten salts of 17,5 equivalent hours at nominal conditions, allowing for a 24/7 electric baseload production (Tab. 1Tab. 4).

Tab. 1	. Key	performance	indicators	for a	commercial	TES
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Key performance indicator		Value	Unit
KPI - 1	Capacity	4,695	MWh
KPI – 2	Charge and discharge time	17.5	hours
KPI – 3	Nominal operating temperature range	290-565	°C
KPI-4	Efficiency	>99.5	%
KPI – 5	Cost	< 20	c€/kWht
KPI - 6	Environmental impact	1.16.104	kgCO ₂ eq./MW _{th}

4. Conclusions

This study reports a first selection of KPIs that can be used for the comparison between innovative thermal energy storage technologies and actual commercial solutions. The selection was done based on the literature available on thermal energy storage considering the requirements of stakeholders involved in the installation and maintenance of CSP plants. A list of six basic KPIs was reported and calculated for a commercial operating CSP plant with a capacity of 110 MW, containing a storage system based on a two-tank molten salt configuration that uses solar salt (mixture of 60wt.% NaNO₃ and 40wt.% KNO₃) with a maximum operating temperature of 565 °C as storage material. The KPIs selected include capacity, operating temperature, efficiency, charge and discharge time, cost, and environmental impact. Nevertheless, other additional key performance indicators can be defined for future comparison of energy storage solutions in CSP applications considering the requirements of the new key role that thermal storage has in the energy market and also indicators at different level. The values calculated for the thermal energy storage of the commercial plant reported in this study can be used as benchmark to compare different TES technologies and to set the target for the research and development of future storage solutions.

5. Acknowledgments

CSPplus is supported under the umbrella of CSP-ERA-Net 1st Cofund Joint Call by AEI - Spanish Ministry of Science, Innovation and Universities, TÜBITAK - Scientific and Technological Research Council of Turkey, and CSO - Israeli Ministry of Energy. CSP-ERA-Net is supported by the European Commission within the EU Framework Programme for Research and Innovation HORIZON 2020 (Cofund ERA-NET Action, N° 838311) and this work was partially funded by Agencia Estatal de Investigación (AEI) - Ministerio de Ciencia, Innovación y Universidades (PCI2020-120695-2/AEI/10.13039/501100011033), and Ministerio de Ciencia, Innovación y Universidades de España (RTI2018-093849-B-C31 - MCIU/AEI/FEDER, UE) and by the Ministerio de Ciencia, Innovación y Universidades-Agencia Estatal de Investigación (AEI) (RED2018-102431-T- AEI). This work is partially supported by ICREA under the ICREA Academia programme. The authors would like to thank the Catalan Government for the quality accreditation given to their research group (2017 SGR 1537). GREiA is certified agent TECNIO in the category of technology developers from the Government of Catalonia.

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Energetic Assessment of a High Temperature Packed Bed Storage System in Combination with a Solar Expanding-Vortex Particle Receiver

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Abstract

A set of packed bed storage systems configured to provide high temperature air has been analyzed at around 1000°C for industrial applications, such as the calcination of alumina. In this study, a solar expanding-vortex particle receiver is selected to provide high temperature air to the storage system. The heat is then used to a drive a continuous industrial process. To ensure the uninterrupted heat supply to the process the system is hybridized with a back-up combustion heater. The main constraint of using a solar expanding vortex receiver is the management of pressure inside the receiver cavity. This is because the receiver has an open aperture, which requires a slight negative pressure to minimize particle egress as well as to maintain the stability of vortex flow inside the receiver. The complete system consists of four subsystems, namely the heliostat field, the receiver, the storage system and the process, which are simulated separately. The feasibility of such a system is explored in terms of energy shares that can be delivered by concentrated solar thermal energy. Furthermore, a preliminary techno-economic assessment is performed estimating the levelized cost of heat as well as the capacity cost of the storage system.

Keywords: high temperature, industrial process heat, solar vortex receiver, Solar Heat for Industrial Processes (SHIP), thermocline storage, hybrid energy systems

1. Introduction

Many industrial chemical processes, such as the calcination of lime and alumina, require temperatures above 1000°C. Due to the high temperature and the complexity of the various industrial processes, these belong to the class of hard to abate emissions (Bataille et al., 2018). Lime and alumina calcination use hot gas as the heat transfer medium, to which heat is presently provided by combustion of natural gas. In the context of seeking to reduce dependency on natural gas, it is desirable to use renewable energy to heat air to sufficiently high temperatures above 1000°C and displace some of the combustion processes. With current commercial solar thermal technology, as used for electricity production in solar tower systems, these temperatures are not achievable due to thermo-chemical limitations of the heat transport fluids, typically being thermal oils or molten salts (Reddy, 2011) (Zarza Moya, 2017). To reach these high temperatures, there are four classes of novel particle receiver concepts under development: the centrifugal drum receiver (Ebert et al., 2019), the falling particle curtain receiver (Ho et al., 2014), the solar expanding-vortex particle receiver (SEVR) (Chinnici et al., 2017) and the fluidized bed linear particle solar receiver (Tregambi et al., 2019). The first two concepts collect the heat exclusively in the particles, whereas in the latter two concepts are a combined medium of a carrier gas laden with particles. All four concepts have shown the potential to reach high temperatures and are also potentially configurable as air heaters. However,

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the components, controls and systems needed to achieve this is different for each case and little information is available regarding how to integrate such systems into an industrial process (Kumar et al., 2019), or how to achieve effective storage of the heat (Gasia et al., 2017).

In this paper we analyze the potential of using a SEVR combined with a set of thermocline storage devices to feed hot air to an alumina calciner. The main focus of this paper is the description and analysis of the storage system. The energetic and economic performance of the complete system, as well as that of the storage system, are modelled and discussed. Solar thermal systems are highly complex and involve multiple components of different cost. It is impossible to optimize these without a system-level, techno-economic model. The aim of the paper is to demonstrate such a model for a reference configuration. The system is not yet optimal, indeed the model will be used to perform such optimizations in the future.

2. Method

2.1 Description of the system

Fig 1 presents the complete system. It consists of four subsystems that are modelled individually, namely the heliostat field, the solar receiver, the storage system and the process. The heliostat field is indicated by the sun symbol, feeding into the receiver, including a system to separate the hot air from the particles. These two systems are referred to as the concentrating solar thermal system (CST). The receiver in turn, feeds hot air into the storage system. The storage system consist of a set of thermocline devices. From the storage system hot air is fed via a backup heater into the process. In this study the subsystems were designed and modelled separately and are described in the following.



Fig 1 The system consists of a heliostat field, the solar expanding vortex receiver, including a system to separate the particulate and gaseous phase of the heat transfer medium, a set of storage devices and a backup system leading to the calcination process.

The heliostat field subsystem was modelled using Heliosim (Potter et al., 2018). Weather data from Western Australia was used to design the optimal heliostat field layout and tower height for a SEVR with nominal thermal capacity of 50MW and aperture radius of 2.75m. Tower heights between 60 and 120m were considered, and preliminary levelized cost of heat (LCOH) values for the solar concentration system were computed using a simple cost model independent from the complete system. The 5 parameters describing the radially staggered heliostat field layout (see Figure3a) were optimized using COBYLA from the NLOpt library (Johnson, 2021) where the objective function is annual optical efficiency. The optimized solar concentration system configuration with a tower height of 80m is shown in Fig 2 and Fig 3. The annual time series of solar power through the aperture for this configuration was calculated using radial basis function interpolation between a set of annually-representative sun positions. This annual time series is then fed as an input into the receiver model.



Fig 2 Visualization of the optimized heliostat field layout, tower height (80m) and SEVR geometry using Heliosim (Potter et al., 2018)



Fig 3 Radially staggered heliostat field layout optimized using Heliosim (Potter et al., 2018)

The SEVR is a type of direct air receiver in which an air vortex within the receiver cavity is established. Air with particles in suspension enters the cavity in a conical entry and travels through the vortex to the opposite end of the cavity where it leaves the receiver through a radial exit near an open aperture (Chinnici et al., 2015). The behaviour of the SEVR is modelled using a zero-dimensional transient model (Rafique et al., 2021). The energy flows through the cavity are modelled, where the particle and gas phases, thermal losses and heat transfer between the different phases and the cavity are considered. The following assumptions and simplifications were employed:

- The solar optical input is considered to be uniformly in the cavity.
- The particles and air are uniformly distributed in the cavity.
- Gas and particles flow through the cavity with minimal recirculation
- Particles all have equal size and follow the gas flow
- Solar radiation is only absorbed by the particles and the refractory lining.

The governing equation for the model reads:

$$\dot{Q}_{sol,ap-w} = \dot{Q}_{thermal} + \dot{Q}_{rad,p-w} + \dot{Q}_{conv,w-a} + \dot{Q}_{cond,w-s} + \dot{Q}_{conv,w-s} + \dot{Q}_{re-rad,w-s}, \qquad (eq. 1)$$

where $\dot{Q}_{sol,ap-w}$ is the optical heat input through the aperture to the inside surface of the cavity walls, $\dot{Q}_{thermal}$ is the heat change of receiver cavity walls, $\dot{Q}_{rad,p-w}$ is the radiative heat exchange between cavity walls and particle phase, $\dot{Q}_{conv,w-a}$ is the convective heat exchange between cavity walls and the air, $\dot{Q}_{cond,w-s}$, $\dot{Q}_{conv,w-s}$ and $\dot{Q}_{re-rad,w-s}$ are the conductive, convective re-radiative heat loss to the surroundings. Fig 4 presents the receiver cavity and the different heat flux components in the receiver cavity. The air particle mixture is fed into a system of cyclones which separates the particles from the air, only the air is then fed to the storage system and the particles are recycled into the receiver.



Fig 4 Schematic view of the solar expanding vortex particle receiver with all heat transfer mechanism considered in the model, where $\dot{Q}_{sol,ap-w}$ is the optical heat input through the aperture to the inside surface of the cavity walls, $\dot{Q}_{thermal}$ is the heat change of receiver cavity walls, $\dot{Q}_{rad,p-w}$ is the radiative heat exchange between cavity walls and particle phase, $\dot{Q}_{conv,w-a}$ is the convective heat exchange between cavity walls and the air, $\dot{Q}_{cond,w-s}$, $\dot{Q}_{conv,w-s}$ and $\dot{Q}_{re-rad,w-s}$ are the conductive, convective re-radiative heat losses to the surroundings.

The reaction in the alumina calcination process is the conversion of gibbsite (aluminum hydroxide) into smelter grade alumina in two steps, see equations (eq. 2) and (eq. 3).

$2Al(OH)_3 \rightarrow 2AlOOH + 2H_2O \qquad (I$	$\Delta H_1 = 1.08 MJ / kg_{Al_2O_2}$), (eq. 2)
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$$2AlOOH \to Al_2O_3 + H_2O \qquad (\Delta H_2 = 0.73 \, MJ / kg_{Al_2O_3}), \qquad (eq. 3)$$

where ΔH_1 and ΔH_2 are the reaction enthalpies for the two reactions. As the process is about 60% efficient the total specific energy per produced kilogram of alumina amounts to 3 *MJ*/*kg*_{*Al*₂0₃}. The calcination of alumina takes place at 950°C in the current process. The heat from the solar system is fed into the process in the air preheater, which limits the energy share that can be provided to the whole process. Detailed questions regarding the process and the process integration are not discussed in this paper. The process is instead simplified as a heat sink with a constant heat duty with a temperature demand of 1000°C and a return temperature of 700°C. If the heat from the storage system is not sufficient to drive the process, a backup system is assumed to provide the missing part. As the optimization of the heliostat field is numerically expensive it was decided to vary the heat demand of the process between 20MW_{th} and 25MW_{th} to simulate different solar multiples. A full optimization is not possible at this stage but an optimal reference system can be chosen from the simulated configurations

2.2 The storage system model

The storage system consists of a set of thermocline storage devices, as shown in Fig 5. Each device consists of an insulated cylinder containing the storage medium. The storage is charged using hot air from the receiver as the heat transport medium. The storage medium is a packed bed of alumina balls, which is enclosed by a layer of fire bricks. Further ceramic fibers are applied as insulation, and a concrete wall encapsulates the whole system. A similar system for particle storage was proposed previously (Ma et al., 2020). The dimension of the different parts

of the containing wall used in the system are summarized in Tab 1. The height H of the storage will be optimized to find the largest solar share for each of the process sizes considered.



Fig 5: The storage medium is a packed bed of alumina balls, which is enclosed by a layer of fire bricks. Further ceramic fibers are applied as insulation and a concrete wall encapsulates the whole system. Radii are given in Tab 1.

Tab 1: Dimension of a single storage device consisting of the storage medium and the insulation materials

Material	Radius
Alumina spheres (storage	$r_1 = 2.5m$
medium)	
Fire brick insulation	$r_2 = 2.8m$
material)	
Ceramic fibre insulation	$r_3 = 4.8m$
material)	
Concrete (outer shell)	$r_4 = 5.1 m$

The model used to describe the storage system is a simplified one dimensional, one phase model. It is computationally sufficiently efficient to allow fast calculation of yearly performance and still captures the most important physical properties of the storage device, namely the movement of the thermocline zone during charging and discharging. The model is described in detail previously (Hoffmann et al., 2016). The partial differential equation at the core of the model reads

$$(\rho C_p)_{eff} \frac{\partial T}{\partial t} + \varepsilon (\rho C_p)_{HTF} u \frac{\partial T}{\partial x} = k_{eff} \frac{\partial^2 T}{\partial x^2} + U_{tot} \frac{A}{V} (T - T_{ext}), \qquad (eq. 4)$$

where the heat capacities are given as $(\rho C_p)_{eff} = \varepsilon (\rho C_p)_{HTF} + (1 - \varepsilon) (\rho C_p)_{stor}$, with ε =0.4 being the mean void fraction for spherical particles (Benyahia and O'Neill, 2005) in a packed bed. The heat conductivity is computed as $k_{eff} = \varepsilon k_{HTF} + (1 - \varepsilon)k_{stor}$, and *u* being the fluid velocity. It is assumed that the temperature *T* is the same for the storage medium and the heat transfer fluid (HTF), this assumption is discussed and verified in (Hoffmann et al., 2016). The heat loss to the environment is described with the parameter U_{tot} and is computed using the wall parameters describes in Tab 1.

To validate the model for a single storage tank experimental data from literature was used (Meier et al., 1991). The key dimensions of the experimental setup are: diameter = 0.15 m, storage height = 1.2 m, mass flow rate = 0.004 kg/s, porosity = 0.36 and the operating temperatures $T_{low} = 21^{\circ}C$ and $T_{high} = 550^{\circ}C$. The storage temperature was measured at 7 positions along in the centre of the device along the axis of the cylinder. The results of the simulation validation is shown in Fig 6, and indicate a good agreement between model and experimental data. The complete storage system consists of a set of thermocline storage devices, that are each described by the model defined in equation (eq. 4).



Fig 6 Simulated (solid lines) results for the thermocline storage device compared with the experimental (x) data taken from Meier et al. (1991)

2.3 The complete system model and operating strategy

To ensure the stability of the particle air vortex and to reduce particle egress through the aperture it is essential to keep the pressure and velocity within the SEVR constant. To assure this the system consists of two separate cycles, namely a charging and a discharging cycle, see Fig 1. In the charging cycle, the hot air from the receiver is fed into the storage system at a constant flow rate, to keep the receiver within constant operating parameters. Once one of the tanks is fully charged it will be switched to the discharge mode to supply heat to the process. Maintaining the charging and discharging cycles separately to allow independently manage the pressure in the receiver. To control all storage devices the temperatures at the top (inlet during charging / outlet during discharge) and at the bottom (outlet during charging / inlet during discharge) need to be measured in both the model and the real system. The operating strategy was chosen to be temperature based and will be optimized in future work. An empty or half empty storage device receives hot air from the receiver as soon as the air temperature is above the low storage set point. Then, it is charged until the temperature of the bottom of the tank reaches the charging set point. When one device is full it starts to be discharged and the next device will receive power from the solar system.

3. Results

3.1. Energetic performance

The simulation was performed for two different values of solar multiple, 2 and 2.5. The solar multiple is defined as the ratio between nominal optical solar input power and process heat demand. As the computation of different solar fields and their output for every time step is time intensive it, was decided to change the process demand instead. For a nominal optical solar input of 50MW the process heat demand was set to $25MW_{th}$ and $20MW_{th}$ respectively. Solar data was used from a location in Western Australia. The air flow through the receiver was fixed at 70.8kg/s, with a particle mass loading ratio of 10%, to reach a receiver temperature of 1100° C for nominal conditions. The process return temperature was set at 700°C. Preliminary results to visualise the storage behaviour, are shown in Fig 7 and Fig 8. Here, a system with a solar multiple of two, consisting of two storage devices with height of 13 meter (2 x 80.8MWh), was used to demonstrate the effect of the control strategy. The state of charge for the two active devices is shown in Fig 8. The fact that the state of charge is below zero at times is due to the heat losses during empty idling. The device is considered empty at 700°C. At such high temperatures the losses to the environment are not trivial.

Interestingly, in all performed simulations only two storage devices were required. To test this behaviour a set of yearly simulations were performed, with the results that the third storage device was never charged, independently from the size of the storage devices, due to the charging strategy allowing to recharge half empty devices, as long as another device can feed the process.





Fig 7: Power flow in the system with a solar multiple of 2, the blue line denotes the power flow from the receiver to the storage system, the red line shows the discharge from the storage system into the process, the yellow line shows the process demand, whereas the purple line shows the nominal receiver power.

Fig 8 State of charge of the two utilized storage devices, the recharging of half full devices causes the switching between the two devices and causes fluctuations in the system

To assess an energetically optimal storage size, 14 days in summer were used to test 10 different storage device sizes (from 18.6MWh to 130.6 MWh in equidistance steps). The system consists of two storage devices. The solar share is defined as the ratio of energy delivered to the process and the process demand over a given period. The simulated solar share over the 14 day period in summer is shown in Fig 9. Interestingly the solar share rises only to certain point, after which it drops off again. This behaviour is expected, considering that the process is only ever fed from a discharging storage. Hence a very large storage device will delay the discharge and the heat has more time to be lost in the storage. For a solar multiple of two a maximal solar share of 38.8% was reached for two storage devices of 82.8MWh each, which translates to a storage height of 13.3 m for each device in the test period. For a solar multiple of 2.5, the maximal solar share in the test period is 44.0%, for a device nominal capacity of 90.4MWh and a storage height for each device of 14.5m.



Fig 9: Solar share as a function storage size of each device. Two devices were active during the simulated time frame.

After the optimization of the storage device size, the two systems were simulated for a whole year and the results are shown in Tab 2. All the energy produced by the CST system is fed into the storage without energy spillage. The average annual heliostat field efficiency was found to be 53.6% and the average annual receiver efficiency was 73.4% in both cases. Interestingly, the increase of the solar multiple from 2 to 2.5 does not significantly influence the solar share and results in 29.4% to 33.2% solar share. The total energy delivered to the system even decreases from 64.4GWh to 58.2 GWh. This is due to the fact that a smaller process will cause the discharging to take longer and will in turn cause greater losses. This can be seen in the drop in efficiency of the storage devices for the larger solar multiple. A more detailed study analysing more values of the solar multiple would provide information on the solar multiple with the largest solar share.

solar multiple	SM=2	SM=2.5
process heat duty	25 MW	20 MW
total solar energy harvested:	79.8 GWh	79.8 GWh
total energy demand of the process	219 GWh	175.2 GWh
total energy into storage	79.8 GWh	79.8 GWh
total energy to process:	64.4 GWh	58.2 GWh
efficiency of storage	80.7 %	73.0 %
solar share	29.4 %	33.2 %
nominal capacity per device	82.7 MWh or 3.3 h	90.2 MWh or 4.5h
total storage time	6.6 h	9 h

Tab 2 Energetic results of the reference system for two different solar multiples for a location in Western Australia

3.2. Economic performance

The technical and energetic assessment presented in Section 3.1 was used to analyse the economic performance of the systems described. To understand the levelized cost of heat (LCOH) delivered to the process, it is vital to know the storage cost. The component costs were researched via market and literature research. Costs that could not be easily researched in the market were scaled to the appropriate size from Strasser and Selvam, (2014) using the scaling formula:

$$C_1 = C_2 \left(\frac{S_1}{S_2}\right)^{0.65},$$
(5)

where C_i denotes the cost of a system with size S_i . The cost of the different subsystems is summarized in Tab 3. The levelized cost is also shown and computed using

$$LCOH = \frac{f \cdot C + 0}{E},\tag{6}$$

where C is the capital cost O is the operational cost and E is the yearly energy yield and f is the annuity factor

$$f = \frac{d(1+d)^n}{(1+d)^{n-1}},$$
(7)

with the discount rate d and the life time in years n.

Tab 3 summary of the economic analysis, showing the cost of the installed components and operational cost as well as the LCOH and the capacity cost.

solar multiple	SM=2	SM=2.5
capacity cost	49.9 AUD/kWh	48.9 AUD/kWh
(nominal capacity)	(82.7MWh)	(90.2MWh)
total storage cost	AUD 8.3 million	AUD 8.8 million
process connection	AUD 8.6 million	AUD 8.6 million
CST system (heliostat field + receiver)	AUD 46.2 million	AUD 46.2 million
installed cost, entire system	AUD 63.1 million	AUD 63.9 million
OPEX	AUD 2.4 million	AUD 2.4 million
LCOH	168.8 AUD/MWh	188.3 AUD/MWh

The storage capacity cost is found to be AUD 49.9/kWh and AUD 48.9/kWh for the SM=2 and 2.5, respectively. Due to the weight of the storage, the main cost driver of the storage system are the foundations, making up 18.3% of the total storage system costs, followed by the storage material contributing 17.6% and the insulation, contributing 17.2% to the total storage systems cost. The cost of the storage system is approximately 1/8th of the total of the CST system, where the cost of the heliostat field is the main driver contributing 30.8% to the CST cost, followed by the cost for the tower contributing 25.3% of the CST cost. The LCOH is found to be 168.8 and

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188.3 AUD/MWh, respectively. This is comparable to the LCOH of a DLR centrifugal receiver in between 162 and 197.6 AUD/MWh (Lubkoll et al., 2018).

3.3. Conclusions

A system model has been demonstrated that incorporates a detailed model for packed bed storage system. Due to the open aperture of the receiver it is not possible to directly feed the process with hot air. To be able to carefully manage the pressure in tat receiver, all the heat needs to go into the storage before it can be relayed to the process. In this study, no energy spillage was found and the storage round trip efficiency was found to be between 70-80%. The overall solar share can be improved if the energy can be utilized in the process directly, without going through the storage, and only storing the excess energy. This however needs changes in the receiver configuration. The low influence of the solar multiple on the solar share is concerning when larger shares of the energy need to be provided by the solar thermal system

The main driver of the LCOH is the CST system and further optimization is necessary. However, significant reductions in LCOH are expected. The current model will be further improved and used for a full optimization in future work.

Compared to the Australian hydrogen target of 2 AUD/kg, which is equivalent to 60 AUD/MWh, the solar thermal reference solution analysed in this study is about 3 times more expensive. Current levelized cost of electricity from wind and solar are between 36 and 72 AUD/MWh ("Levelized Cost of Energy and of Storage," n.d.). The best case in this study achieves a LCOH of 168.8 AUB/MWh, providing only 29.4% of the yearly process energy demand. This is at least twice as costly as using electricity from solar and wind, which can provide higher renewable shares in combination, even without storage, in some locations. The analysed storage in this study has a very low capacity cost of just under 50AUD/kWh and is more economical than electro-chemical storage systems such as batteries. Thus, the combination of renewable electricity and thermal storage is an interesting option worth investigating.

The problem of decarbonizing high temperature industrial processes is far from being solved and much future investigation into all available technologies, such as solar thermal, hydrogen and electrification has to be done. Further exploration of new chemical production routes to reduce the temperature demand is also necessary to tackle this challenge.

4. Acknowledgments

This project received funding from ARENA through grant 2015/RND054 as part of ARENA's Research and Development Programme.

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Integration of Packed-bed Thermal Energy Storage in Solar Heat System for a Food Industry

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Abstract

Thermal energy storage (TES) is a key technology to increase efficiency of solar energy in industrial applications. Especially, packed-bed TES systems filled with low cost and sustainable sensible thermal energy storage materials (STESMs) decrease the energy cost and provide green industries by increasing use of solar energy. In this study, integration of packed-bed TES system filled with new sustainable and low cost STESMs developed from demolition wastes in a solar heat industrial process (SHIP) was simulated. Potato crisp production process was selected as a case study. Results showed that packed-bed TES system integrated with solar plant could provide 39.2 % saving in fossil fuel consumption of potato crisp production process.

Keywords: Demolition waste, packed-bed, solar heat industrial applications, thermal energy storage.

1.Introduction

Total energy consumption in the world was 9717 Mtoe in 2019 and industry is the largest energy-consuming sector in the world with 37 % share (IEA, 2019a). Industrial energy systems are mainly based on fossil fuels that causes serious environmental problems mainly air pollution and global warming. One-fifth of the 33 Gt global CO_2 emissions were released to nature by industry in 2019 (IEA, 2019b). World leaders from 130 countries have committed to "keeping the rise in global mean temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial levels." according to Paris agreement in 2017 (UNFCCC, 2015). Renewable energy sources can play an important role in industries to meet long-term climate and other sustainability goals.

Using renewable energy in industrial applications can reduce dependency on fossil fuels, decrease production cost and increase competitiveness in global market. Solar energy is one of the most abundant and eco-friendly renewable source, especially for processes up to 200°C (Koçak et al. 2020). Although, solar heat industrial applications are expected to reduce fuel cost and CO₂ emissions, there are only 741 industrial heat solar plants (SHIP) in the world that supply approximately 567 MW_{th} heat for industrial processes (IEA, 2019c). The current industrial solar use is less than 1% of the worldwide installed solar capacity (IEA, 2019c). Today, solar thermal applications are mainly used in residential, hospitals, shopping malls etc in building sector.

Only drawback is intermittency of solar energy, which necessitates using it with a suitable TES technology (Koçak et al. 2020). TES is a key technology to increase efficiency of solar energy in industrial applications (Koçak et al. 2020). The integration of TES systems using eco-innovative storage materials can increase energy efficiency and sustainability of solar heat industrial applications. Using storage materials based on wastes for energy saving complies with circular economy that is one of the main blocks of European Union Green Deal.

Recent studies focus on reducing fossil fuel consumption in industrial application by integrating TES system in solar heat industrial applications. Packed-bed TES systems filled with cheap and high energy density packing materials are preferable options for industrial applications due to their low cost and high storage capacity (Khare et al., 2013; Alonso et al., 2016; Koçak et al. 2020). Experimental data from lab-scale and pilot scale packed bed TES systems are crucial for potential large scale TES systems in industrial applications. Besides, mathematical models can be used to estimate storage performance and optimum design parameters (Buscemi et al. 2018,

Cardenas et al. 2019, Singh et al. 2019). In our previous studies (Koçak and Paksoy, 2019; 2020; Koçak et al. 2020), new eco-innovative STESM was developed from demolition waste and its performance was evaluated in a lab-scale packed-bed TES system in the temperature range of $130 \text{ }^{\circ}\text{C} - 180 \text{ }^{\circ}\text{C}$.

In this study, a scaled-up simulation study was carried out for a potato crisp production process based on the findings from lab-scale packed-bed TES system filled with new STESM developed from demolition wastes. Economic and environmental impacts were evaluated.

2.Materials and methodology

2.1 Lab-scale TES system

Laboratory scale packed bed TES system was built based on the scheme given in Fig. 1a. The real system given in Fig. 1b consists of a cylindrical storage tank with a height of 0.9 m and diameter of 0.3 m, oil bath, flow meters, oil pump, 2-way and 3-way valves, heat exchanger, heating coil and thermocouples.



Fig. 1: Lab-scale packed-bed TES system

In lab-scale TES system design, packing material developed from demolition waste and Therminol 66 as HTF were used. STESM developed from demolition waste is a potential low-cost STESM for industrial solar applications up to 750°C (Koçak and Paksoy, 2019). Therminol 66 was selected as HTF due to its operation capability in medium temperature range. Lab-scale packed-bed TES system properties are listed in Table 1 (Koçak and Paksoy, 2020). Thermal energy storage experiments were carried out in fluid temperature range of 80 - 180 °C for charging and fluid flow rate from 50 kgh⁻¹ to 750 kgh⁻¹. At the optimum operating conditions, system energy efficiency reached to 65%.

Parameter	Value	Unit
Height of storage tank; h _{tank}	0.9	m
Diameter of storage tank; D _{tank} (m)	0.3	m
Inlet temperature range; T _{in}	80-180	°C
Bed void fraction, ε	0.39	-
Diameter of solid; D _s	0.01	М
Fluid flow rate; m	50-750	kgh ⁻¹
Charging temperature; T _{charge}	240	°C
Discharging temperature; T _{discharge}	180	°C
Density of solid; ps,	2855	kgm ⁻³
Specific heat of solid, Cp _s	1450	Jkg ⁻¹ C ⁻¹
Density of HTF; p _f	889 @ 180 °C	kgm ⁻³
Specific heat of HTF; Cp _f	2120 @180 °C	Jkg ⁻¹ C ⁻¹
Maximum System Energy Efficiency, η_{sys}	65	%

2.2. Potato frying crisp process as a case study

Based on data obtained from lab-scale TES system, integration of large scale TES system in an industrial plant was investigated. For this purpose, a potato crisp frying process was selected as case study. Economic and environmental impacts of TES systems in potato crisp process were evaluated through 3 case studies given below.

2.2.1 Case 1: Current energy system

Current energy system of potato frying process studied previously by Wu et al (2012, 2013) was taken as the reference system. In the process shown in Fig. 2, raw potatoes are fed to the fryer at a flow rate of 1.0 kgs⁻¹ to produce crisp potatoes at a flow rate of 0.28 kgs⁻¹. Hot sunflower oil at a range of 170-190 °C is circulated through the fryer. At the exit of the fryer, fresh sunflower oil is added to make up for the loss during frying. Combined oil at approximately 155 °C is sent to the heat exchanger. Combustion products flow through the heat exchanger to heat oil coming from fryer. After heat exchange, hot oil at approximately at 173 °C is returned to the fryer.



Fig.2: Energy supply diagram for case 1

2.2.2 Case 2: Integration of solar plant in potato crisp frying process

In case 2, solar energy integration in potato crisp production process was simulated as an alternative energy source. It was assumed that industrial plant is located in Adana, Turkey. According to data from Turkish Meteorological Service, average daily hours of sunshine are 7.5 hours in Adana (www.mgm.gov.tr). Solitem PTC4000 parabolic trough collector was selected as suitable collector type due to the process temperature range up to 250 °C and high efficiency (up to 75%). Considering annual average direct normal irradiation (DNI) value for Adana is 1900 kWhm⁻² per year, the gross collector area needed for potato crisp process was found as 5870 m² (Koçak, 2020).

2.2.3 Case 3: Integration of TES system in potato crisp frying process

In case 3, integration of packed-bed TES system with solar heat in potato crisp production process was evaluated as an alternative energy source. In TES system design, packing material developed from demolition waste and Therminol 66 as HTF were used. Industrial scale TES system properties are listed in Tab. 2 based on the data from lab-scale system.

Working principle of industrial scale packed-bed TES system is same with the lab-scale storage system. During the charging step, hot HTF enters top of the storage tank. Storage media absorbs heat from the hot HTF and HTF leaves from bottom of the tank. During the discharging step, cold HTF coming from HEX enters through bottom of the storage tank and hot packing materials release heat to the HTF. As a result, hot HTF leaves from top of the tank to provide heat to the process.

Parameter	Value	Unit
Bed void fraction, ε	0.39	-
Energy System Efficiency, η_{sys}	65	%
Charging temperature, T _{charge}	240	°C
Discharging temperature, T _{discharge}	180	°C
Density of solid, ps	2855	kgm ⁻³
Specific heat of solid, Cps	1450	Jkg ⁻¹ C ⁻¹
Density of HTF, ρ_f	840 @ 240 °C	kgm ⁻³
Specific heat of HTF; Cp _f	2340 @240 °C	Jkg ⁻¹ C ⁻¹
Mass of components of system, m _{comp}	13	ton
Specific heat of components of system, Cp _{comp}	460	Jkg ⁻¹ C ⁻¹

Tab. 2: Prop	perties of	industrial	scale	TES	system
140.2.110	per mes or	maastim	beare	110	System

3.Results and discussion

Average energy requirement to increase frying oil temperature from 155 °C to 173 °C is 2650 kW. Energy requirement for process is supplied from a natural gas combustion system with an efficiency of 84%. Therefore, the combustor should have an average energy capacity of 3150 kW (Wu et al. 2012; 2013).

It was assumed that potato crisp frying process is working for 24 hours per day and 5 days per week. Considering working period, annual heat consumption for potato frying crisp process is 16.7 GW.

In case 2, 5870 m² solar plant was integrated in potato crisp frying process. The diagram of the solar system is shown in Fig. 3. Therminol 66 is selected as HTF due to its operation capability for medium temperature range. A shell and tube heat exchanger (HEX) with 90 % efficiency is used in the system to transfer heat from Therminol 66 to frying oil. Combustor system is still available in frying process as an axillary heater to provide heat when solar energy is not available or not enough.



Fig. 3: Energy flow diagram for case 2

Although potato crisp frying process is shut down during weekends, solar system is operated 7 days per week. 7.85 GWh energy can be provided from 5870 m^2 PTC4000 solar field by operating 360 days per year with 1900 kWh/m² of DNI and average 7.5 hours of sunshine. 5.15 GWh of the available solar energy can only be provided

for the process heating (Koçak, 2020). This is 29.8 % of annual total heat consumption of potato frying crisp process. The rest of 2.7 GWh can be stored in packed bed to be used later.

In case 3, packed-bed TES system was integrated into potato crisp frying process to increase efficiency of solar system. Fig.4 gives flow diagram for solar heat and TES integration in potato crisp process.



Fig. 4: Energy flow diagram for case s3

Maximum energy (E_{max}) that can be stored in the packed-bed system is the sum of energy stored in solid phase, fluid phase and other components of the system such as tank walls, filters etc. E_{max} can be calculated using Eq. 1 (IEA-ECES, 2018). According to Eq. 1, storage volume (V_{tank}) of 200 m³ is needed to store annual excess heat of 2.7 GWh.

$$E_{max} = \int_{T_{in}}^{T_{out}} [V_{tank} (\varepsilon \rho_f(T) C p_f(T) + (1 - \varepsilon) \rho_s C p_s) + m_{comp} C p_{comp}] dT \quad (eq. 1)$$

Efficiency, the ratio of discharged energy (E_D) to charged energy (E_C) , is calculated with Eq. 2 (Bruch et al. 2017)

$$\eta_E = \frac{E_D}{E_C} \tag{eq. 2}$$

Efficiency of packed bed storage system is assumed to be 65 % basd the experimental results of the lab-scale system (Koçak and Paksoy, 2020). Packed-bed storage system with this efficiency can provide 1.75 GWh energy per year. 90% of 1.75 GWh energy can be utilized by HEX. Hence, 1.58 GWh energy from TES system can be used for process heating.

As a result, packed-bed TES system with a volume of 200 m^3 increased the solar energy efficiency from 29.8 % to 39.2 %. This leads to reduction of total annual energy supply from combustor system from 11.7 GWh to 10.1 GWh.

Economic and environmental impacts of the TES system in this industrial application were evaluated for the case studies and shown in Tab. 2. Potato frying process analyzed as case study consumes 16.7 GWh energy per year for fryer oil heating. In this energy system used currently, process heat demand is totally provided from combustion system burning natural gas. According to natural gas provider company BOTAŞ, industrial natural gas price per unit consumption is $0.20 \notin m^3$ for 2021. As a result, annual natural gas consumption price of case 1 is 380000 Euro excluding tax. Besides high energy cost, natural gas burning causes high amount of greenhouse gas emissions. According to EPA, CO₂ emission factor for natural gas combustion is $1.92 \text{ kg CO}_2\text{m}^{-3}$. As a result, greenhouse gas emissions released to nature is 3650 tons.

5.0 GWh of process heat demand is supplied from Solitem PTC4000 solar field that has 5870 m² gross collector area. This provides 29.8% saving in both annual energy price and CO₂ emissions. Annual energy cost decreases from $380000 \notin$ to $267000 \notin$ and CO₂ emissions decreases from 3650 ton CO₂ per year to 2650 ton CO₂ per year.

Thermal energy storage systems increase the efficiency of solar systems by storing surplus solar heat. In case 3, energy efficiency reaches to 39.2 % by integrating 200 m³ volume packed-bed TES system. Totally, 6.58 GWh energy can be provided from solar system. This energy represents CO_2 emissions reduction of 1430 tons per year. Besides, 148700 \notin saved per year.

rab. 5. Economic and environmental impacts of case studies						
Parameters	Case 1	Case 2	Case 3	Unit		
Process Energy Demand	16.7	16.7	16.7	GWh		
Energy supplied from combustor	16.7	11.7	10.1	GWh		
Energy supplied from solar field	-	5.0	5.0	GWh		
Energy supplied from TES	-	-	1.58	GWh		
Natural gas consumption amount	1900800	1334150	1156430	m ³ /year		
Natural gas consumption cost	380000	267000	231300	€/year		
Cost saving	-	113000	148700	€/year		
CO ₂ emissions	3650	2560	2220	ton CO ₂ /year		
Saving	-	29.8	39.2	%		

Tab. 3: Economic and environmental impacts of case studies

4.Conclusion

Thermal energy storage systems increase the efficiency of solar systems by storing surplus solar heat. Sustainability aspects of STESM make TES systems more favorable and allow using energy according to circular economy principles. In the case study given here, energy efficiency of solar system was increased from 29.8 % to 39.2 % by integrating packed-bed TES system filled with STESMs developed from demolition waste. Natural gas consumption and hence CO₂ emissions were also reduced. Also, valorization of demolition waste as STESM is a sustainable approach in reducing fossil fuel consumption of industrial applications and avoiding the use of natural resources as packing material.

5.Acknowledgments

The Autors would like to thank TUBITAK Project (No:218M182) and CSP-ERA-Net 1st Cofund Joint Call by AEI - Spanish Ministry of Science, Innovation and Universities, TUBITAK - Scientific and Technological Research Council of Turkey (Project No:120N663), and CSO - Israeli Ministry of Energy. CSP-ERA-Net is supported by the European Commission within the EU Framework Program for Research and Innovation HORIZON 2020 (Cofund ERA-NET Action, N° 838311).

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Lab-Scale Reactor Tests on Fe-Doped CaMnO₃ for Thermochemical Heat Storage Application

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Abstract

In order to improve the dispatchability of next-generation concentrated solar power (CSP) plants, $Ca(Fe_{0.1}M_{0.9})O_3$ has been proposed as high temperature (>800 °C) thermochemical energy storage (TES) materials. Only recently, the thermodynamics of $Ca(Fe_{0.1}M_{0.9})O_3$ oxide has been measured through Van't Hoff approach via thermogravimetric (TG) analysis, thus allowing access to the oxygen non-stoichiometry profiles ($\delta(T, pO_2)$) under different temperature and oxygen partial pressure pO₂. The material TES performance is here investigated through laboratory scale reactor tests carried out under conditions considered representative of future CSP plants. Remarkably, the material exhibits the same $\delta(T, pO_2)$ profile as the one computed from the thermodynamics at a significantly larger scale (~40g). According to the obtained results, $Ca(Fe_{0.1}M_{0.9})O_3$ oxide appears ideally suited for thermal energy storage applications with a large total (thermochemical and sensible) heat storage capacity (~916 kJ/kg_{ABO3}) and good scalability.

Keywords: thermal energy storage, reactor tests, perovskite, calcium manganite, iron doping.

1. Introduction

Widespread adoption of concentrating solar power (CSP) plants depends considerably on (i) how efficiently solar energy is transformed in electricity collected by means of thermodynamic cycles and (ii) the ability of the plant to store energy and supply power on demand during off-sun periods. The heat-to-electricity conversion efficiency can be enhanced through advanced thermodynamic based on Brayton (*i.e.* sCO₂) or combined cycles (*i.e.* air) (Weinstein et al. (2015)), thus requiring high operating temperatures (\geq 800°C up to 1200 °C). The latter can be put into effect with Thermal Energy Storage (TES) systems. The benefit of high operating temperatures makes a compelling case for designing high-temperature (\geq 800°C) heat storage systems. TES technologies can be categorized into sensible (latent) heat storage and thermochemical heat storage (TCS). In TCS systems, heat is converted into chemical energy by promoting an endothermic reaction whereby reaction products are stored for a later re-use in the reverse reaction. Different reaction pairs are used to store heat depending on the heat storage target temperature (André et al. (2016)). Additionally, the selection of a proper system is determined by the overall thermodynamic performance and by chemical engineering criteria (kinetics, design factors, etc.), which determine practicability and cost of operation.

Recently, it has been demonstrated that perovskites (ABO₃) are promising candidates for high-temperature ThermoChemical heat storage (TCS) applications. A perovskite-based TES system is based on the following reaction:

$$ABO_{3-\delta_i}(s) \rightleftharpoons ABO_{3-\delta_f}(s) + \frac{\delta_{f} \delta_i}{2}O_2(g)$$
 (eq. 1)

where, δ_0 is the initial oxygen nonstoichiometry, and δ_f is the nonstoichiometry at the completion of the reduction/oxidation process. The ABO₃ oxide reduction/oxidation reaction can occur through continuous oxygen release/uptake over a broad temperature window with the formation/destruction of oxygen vacancies within the material's structure.

Babiniec et al. studied $La_xSr_{1-x}Co_yM_{1-y}O_{3-\delta}$ (M=Mn, Fe) compositions, with $0.1 \le x \le 0.9$ and $0.1 \le y \le 0.9$ (Babiniec et al. (2015)). They showed interesting heat storage capacity and placed this class of materials among the candidates for high-temperature TES systems. The potential of SrBO_{3-\delta} and BaBO_{3-\delta} (B=Mn, Fe, Co) oxides as TES materials

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has been investigated by Zhang and co-workers (Zhang et al. (2016)). The analogous material, CaMnO₃, has attracted high interest because, being based on earth-abundant elements, it is cost-effective (Babiniec et al. (2015), Imponenti et al (2017), Mastronardo et al. (2020), Torres et al. (2019)). B-site doping with Fe (Mastronardo et al (2020), Mastronardo et al. (2019)), Al (Babiniec et al. (2015)), Ti (Babiniec et al. (2015)), Co (Jin et al. (2021)) and Cr (Lucio et al. (2019)) enhanced the heat storage capacity relative to that of undoped CaMnO₃. Of these materials, Ca(Fe_{0.1}Mn_{0.9})O₃ has been studied by thermogravimetric analysis (TGA) and its thermodynamics determined through the Van't Hoff approach (Mastronardo et al. (2020)). In comparison to other dopants, Fe enables operation at higher temperature and more moderate pO_2 for a comparable level of heat storage (Mastronardo et al (2020), Mastronardo et al. (2019)). Additionally, its stability was assessed by long-term (~80h) cycling between reduction and subsequent reoxidation to simulate the operating conditions. These attractive features warranted further investigation. Indeed, large scale reactor tests are fundamental to bring the perovskites TCS systems to a level closer to the market (Pan et al. (2017)). In this regard, several research activities are focused on design and development of TES pilot plant tests (Jackson et al. (2019), Schrader et al. (2020)).

We carry out here an evaluation of $Ca(Fe_{0.1}Mn_{0.9})O_3$ heat storage performance through lab-scale reactor tests at significantly larger scale than previously reported and under conditions considered realistic according to the design features of future power plants.

2. Materials and Methods

2.1 Material preparation and characterization

About 40 g of Ca(Fe_{0.1}Mn_{0.9})O₃ oxide, hereafter CMF91, was prepared according to a modified Pechini method reported in the literature (Mastronardo et al. (2020)). The CMF91 powder was mixed and ground with 5% wt. of carboxymethylcellulose (CMC), and then mixed with a specific amount of water to obtain a plastic paste. The paste was extruded through a cylindrical die of 0.3mm Ø and cut into pieces of ~1 cm length. The pellets were sintered at 1100 °C (heating/cooling rate 3°C/min) for 8h under static air and the CMC fully decomposed (verified by X-Ray Diffraction – XRD – analysis). The resulting porous CMF91 pellets were characterized by Mercury Intrusion Porosimetry (MIP) analysis and Scanning Electron Microscopy (SEM).

2.2 Lab-scale reactor apparatus and tests

The lab-scale reactor for testing heat storage suitability (Figure 1) consists of a customized high-temperature furnace, an alumina reactor tube (length 1.2m, $\emptyset_{external}$ 30mm, $\emptyset_{internal}$ 24mm), a cooling system, and a Micro Gas Chromatographer (mGC) that samples the O₂ concentration. The reactor tube is filled from the bottom to a selected height with chunks of alumina foam so that the material bed is allocated in the furnace's middle isothermal zone. The supplied gas flows from the top to the bottom of the tubular reactor and is analyzed through the mGC. In a typical experiment, the material is heated up to a selected reduction temperature (T_r), and, after a hold time of 30 minutes, it is cooled down to the oxidation temperature (T_o). Several tests were carried out varying pO₂, T_r, and gas flow rate. The O₂ evolution while heating and cooling was measured, and a comparison between δ (T) profiles obtained by lab-scale reactor test (~40 g) and thermogravimetric analysis (~500 mg) was carried out to verify the material's thermochemical performance at a significantly larger mass scale.


Fig. 1: Scheme of the lab-scale reactor apparatus.

In order to calculate the material oxygen evolution profile obtained from the reactor tests, the instant oxygen concentration recorded by mGC analyzer is subtracted from the average supplied O_2 flow concentration:

$$\Delta O_{2i}(\%/\text{min}) = O_{2ist} - O_{2avg} \qquad (eq. 2)$$

The oxygen evolution is converted in mol/min (equ. 3), and the cumulative value is obtained by the integration over time (equ. 4):

$$\Delta O_{2_{i}}\left(\frac{\text{mol}}{\text{min}}\right) = \frac{\Delta O_{2_{i}}(\%/\text{min}) \cdot \dot{V}(\text{nL/min})}{22.4136(\text{mol}^{-1})}$$
(eq. 3)
$$\Delta \text{mO}_{2_{i}}(g) = M_{O_{2}} \cdot \int_{t_{0}}^{t_{i}} \Delta O_{2} dt$$
(eq. 4)

being $\dot{V}(nL/min)$ the total flow rate.

The equilibrium oxygen nonstoichiometry is calculated according to equation 5:

$$3 \cdot \delta_i = 3 \cdot \delta_0 + \left(\frac{\Delta m O_{2_i}}{M_0 \cdot n_{ABO3}}\right)$$
(eq. 5)

where (δ_0) is the material initial oxygen nonstoichiometry at the specific T_o and pO_2 used – extracted from the available thermodynamics data (Mastronardo et al. (2020)) –, M_O (g/mol) is the monoatomic oxygen mass, and n_{ABO3} (mol) are the moles of material.

3. Results and Discussion

Hg porosimetry results are shown in Fig. 2a. The incremental Hg intrusion plot as a function of the pore diameter shows three peaks, all in the macropore range, centered around 2, 4 and 10 μ m, respectively. The Hg intrusion in the low-pressure region (ca. 0.1–10 μ m) is due to the interparticle voids and cracks, which can also be observed on the surface of pellets by SEM analysis (Fig. 2b). The as prepared pellets have a total pore volume and area of 0.36 ml/g and 0.54 m²/g, respectively, a bulk density of 3.58 g/ml, and a porosity of 56% thus guaranteeing easy gas access to the entirety of the material that is an essential feature for eventual technological deployment.



Fig. 2: (a) Incremental intrusion plotted against pore diameter and (b) SEM micrograph of CMF91 pellets prepared with the addition of 5% of CMC.

Fig. 3 shows the comparison between the heating/cooling $\delta(T)$ profiles obtained by lab-scale reactor test and thermogravimetric (TG) analysis previously performed (Mastronardo et al. (2020)). Heating and cooling profiles overlap, indicating complete reversibility. Also, remarkably, the profiles obtained by lab-scale reactor test matches fairly well with the TG profile, indicating results reproducibility using a mass (~40g) two orders of magnitude larger than the one used in TG (~0.5g). Thus, not only does the material releases oxygen up to its thermodynamic limit (determined by the operating conditions), but also it remains equilibrated in the lab-scale reactor environment for the gas flow and heating rates employed.



Fig. 3: δ(T) profiles of CMF91 material determined by mGC and compared to TG analysis profile (Mastronardo et al. (2020)).

The material chemical heat storage capacity is calculated as:

$$Q_{C}\left(\frac{kJ}{kg_{ABO3}}\right) = \frac{1}{M_{ABO3}} \int_{\delta_{i}}^{\delta_{f}} \Delta_{red} h\left(\frac{kJ}{mol_{O}}\right) d\delta \qquad (eq. 6)$$

where M_{ABO3} is the molar mass of the oxide, $\Delta_{red}h$ is the enthalpy of reduction associated with reaction (1) and has been evaluated in a previous thermodynamic study (Mastronardo et al. (2020)), δ_i is the initial oxygen nonstoichiometry (at $T = T_0$) and δ_f is the nonstoichiometry at the final condition of interest, here taken to be $T=T_R$. Using the known thermodynamic properties of CMF91, chemical heat storage capacity of \sim 356 kJ/kg_{ABO3} is estimated. Taking into account the sensible heat, the total heat storage capacity of the material (Q_{tot}) is:

$$Q_{\text{tot}} \left(\frac{kJ}{kg_{\text{ABO3}}}\right) = Q_{\text{C}} + \int_{T_{\text{O}}}^{T_{\text{R}}} C_{\text{P}} dT \qquad (\text{eq. 7})$$

/

where C_p is the material's heat capacity. CMF91 total heat storage capacity in the temperature range 500-1200 °C under a pO₂ of 0.01 atm is ~916 kJ/kg_{ABO3}.



Fig. 4: Total (Qt) and chemical (Qc) heat storage capacity of the material as a function of temperature.

4. Conclusions

The heat storage capacity of CMF91 pellets has been evaluated through a lab-scale thermochemical heat storage reactor. Remarkably, it was evidenced that the material at a significantly larger scale (two orders of magnitude larger) was able to exhibit the same performance than the one measured through thermogravimetric analysis. According to these results, CMF91 appears ideally suited for thermochemical heat storage applications with a high total heat storage capacity (~916 kJ/kg_{ABO3}) and good scalability.

5. Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement N° 74616. Support of the ACES2030 from "Comunidad de Madrid" and European Structural Funds to (P2018/EMT-4319), and of the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Award DE-EE0008089.0000 are also fully acknowledged.

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Modelling of oil based medium temperature sensible heat thermal energy storage systems during charging

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Abstract

A simulation model for oil based medium temperature sensible heat storage systems for domestic solar cooking applications is developed and validated with experimental results. The simulated and experimental results are simultaneously compared for three sensible heat storage systems during charging. The three systems compared are a Sunflower Oil storage tank, a Sunflower Oil/10.5 mm pebbles packed bed storage tank and a Sunflower Oil/31.9 mm pebbles packed bed storage tank. The packed bed TES systems have void fractions of 0.39 and 0.43, respectively. A forward finite difference model is developed in Matlab to simulate the storage systems. Validation of the thermal energy storage (TES) models is done using a flow-rate of 4 mls⁻¹. A good level of agreement exists between simulated and experimental results with an overall mean percentage error (deviation) of 6 % for the Sunflower Oil/31.9 mm pebbles packed bed storage material is investigated with the model. An increase in the flow-rate leads to the faster decrease in the temperature gradients in the TES systems considered. An inlet temperature increase results in faster rises of the storage tank temperatures, and higher maximum temperatures in the storage tanks. Considering the different thermal oils, the best storage performance is seen with Sunflower Oil since it shows better thermal stratification. The best packed bed sensible heat storage material is granite since it shows larger thermal gradients.

Keywords: Charging; Modelling and simulation; Packed bed thermal energy storage; Sunflower Oil

1. Introduction

Energy is essential for the social and economic development of any society (Rehma et al., 2014). Clean energy supply is still limited especially in most developing countries as biomass still serves as the major source of cooking energy. The supply of fossil fuels has also become inadequate for the growing global population which has led to an upward rise in their prices due to their high demand (World Energy Council, 2010). In order to continuously harness and utilize clean and sustainable energy which is not disrupted by low/no sunshine periods, solar thermal energy storage (TES) is essential (Kolb et al., 2011). Thermal energy storage (TES) is an emerging advanced technology for storing thermal energy that can enable more efficient and clean energy utilisation. TES systems developed for domestic applications are practically categorized as latent heat thermal energy storage (LHTES), sensible heat thermal energy storage (SHTES) and thermo-chemical reactions. LHTES is advantageous over SHTES because of its high thermal energy density. Unfortunately, LHTES systems are expensive. LHTES using phase change materials (PCMs) has a challenge of severe degradation with time. PCMs usually have low thermal conductivities and require a longer time to absorb and release the same energy for domestic applications such as cooking. This implies that the larger thermal conductivities of sensible heat materials (SHMs) are important for easy heat transfer in TES systems. Foong et al., (2011) noted that in developing countries where the issue of cost effectiveness and simplicity outweighs the issue of superior thermal performance, SHTES systems are more viable options for small-scale domestic applications like cooking of food. This is because these SHTES systems are cheap to design and easy to fabricate and maintain. Several experimental studies have been conducted on SHTES systems (Bindra et al., 2013). However, scientific work using experiments is expensive and needs a lot of precautions which can be alleviated by developing a simulation model.

Simulation is used to study in detail the dynamics of using different TES configurations and materials in terms of their thermal performance characteristics (Kumar & Rosen, 2010). The classical analytical solution for the heat transfer between a fluid and solids in a packed bed was developed by Schumann, (1929). He used several assumptions of materials. The assumptions included high thermal conductivity inside the solids, low conductivity between solids in axial direction, constant fluid properties, no wall heat losses and no temperature gradient in the radial direction. Another simplified model which basically follows Schumann's model was proposed by Vortmeyer & Schaefer, (1974). This model does not neglect the axial thermal conductivity. The model is useful for systems where the thermal conductivity of the solid phase is much larger than that of the liquid phase, and it combines the two phase models (solid and liquid) into a single phase model. Chikukwa, (2007) modelled a rock bed storage system using the Schumann model and air as the heat transport fluid. Results from the study indicated that rocks could be used to store high temperature heat. Unfortunately, insulation posed a big challenge. Okello et al., (2009) reported an experimental study on high temperature heat storage using rock beds. They presented simulated temperature profiles in the bed during charging and discharging that were similar to the experimental data. Mawire et al., (2008) carried out simulated performances for an oil/pebble packed TES system using a validated model. They reported that thermal stratification, and the total amount of energy and exergy stored were all important parameters for the thermal performance and evaluation of oil/pebble bed storage systems. Lovseth, (1997) proposed a design of a rock bed for high temperature heat storage using solar concentrating systems. What made the system unique was that it was a small scale concentrating system, easy to fabricate, with heat storage for rural food preparation. The study clearly pointed out that further work was needed to achieve a novel system that could be used for cooking. Van-den-Heetkamp (2002) reported on the practical aspects and preliminary results on a rock bed storage system designed for cooking. This study was based on the initial work conducted by Lovseth, (1997). Experimental work and theoretical analysis of the system showed that the system was realistic since the theoretical results were in good agreement with the experimental data. However, it was observed that much work still needed to be done on the system integration of the packed bed. Markus et al., (2011) developed a heat transfer model for high temperature storage using rock beds and air as the HTF. Unfortunately, this study neglected heat transfer by radiation. According to Parameshwarana et al., (2012), the majority of the existing models are applied for low temperatures. These low temperatures are only suitable for space heating using air and water as the storage materials.

The literature available shows that there is very limited work on both modelling and experimental analysis of TES systems designed for cooking using sensible heat materials in the medium temperature ranges using thermal oils. These materials include granite rock pebbles and Sunflower Oil which are widely available in most countries worldwide. The aim of this study is to model oil based medium temperature sensible heat thermal energy storage systems during charging for use in indirect solar cookers. Experimental results of three sensible heat storage systems are used to validate the model namely; (a) A TES system of 7 l of Sunflower Oil (b) a Sunflower Oil/10.5 mm pebble packed bed TES system with a void fraction 0.39, and (c) a Sunflower Oil/31.9 mm pebble packed bed TES system with a void fraction 0.43. A parametric study will be further performed using the experimentally validated model.

2. Mathematical model

A model for predicting the thermal performance of TES systems at medium to high temperatures (100 °C to 300 °C) was developed. The model was based on numerical integration, and was used for the prediction of the thermal profiles in the packed systems for performance optimization. The mathematical model developed using Matlab was used to generate temperatures at each axial node and at new time steps, using an implicit-time matching forward finite difference method. The forward finite difference method was chosen for this study because of the small size of the TES system design where few parameters were considered during simulation. A number of explicit assumptions were made in the formulation of the mathematical model for this study. The assumptions were:

- i. radiant heat transfer in the storage was neglected and the governing equation was a one axial dimensional equation;
- ii. the overall insulation of the system was considered uniform;

- iii. the thermo-physical properties of the pebbles were considered constant and calculated at an average temperature;
- iv. the pebbles were assumed to be identical and that there was no internal heat generation within the bed;
- v. the pebbles were assumed to have a constant volume; and
- vi. the HTF was assumed to be flowing over the rocks with a uniform velocity.

The modified equation from Schumann model (Schumann, 1929) for the heat transfer fluid (HTF) is given as Equation 1;

$$\rho_{S}c_{S}A_{T}L_{T}\epsilon\frac{\partial T}{\partial t} = Q - \rho_{S}c_{S}A_{T}L_{T}\dot{V}\frac{\partial T}{\partial y} - u_{S}\left[T - T_{amb}\right]$$

(eq.1)

, where Q (W) is the heat energy, ρ_s (kgm⁻³) is the density of Sunflower Oil, c_s (Jkg⁻¹K⁻¹) is the specific heat capacity of Sunflower Oil, A_T (m²) is the cross sectional area of the tank, $L_T(m)$ is the height of the storage tank

 ϵ (-) is the void fraction, V (mls⁻¹) is the volumetric flow rate, u_S (WK⁻¹) is the insulation value of the storage tank, T(K) is the temperature of Sunflower Oil, y(m) is the axial coordinate t(s) is the time and T_{amb} (K) is the temperature of the surroundings. The conduction term was not considered in Equation 1 because its effect was negligible as compared to the convection term. Hence convection dominates when a fluid alone was considered for heat transfer/storage. The modified equation from Schumann model for the oil/pebble bed storage system is given as Equation 2;

$$\left[\rho_{S}c_{S}A_{T}L_{T}\varepsilon + \rho_{r}c_{r}A_{T}L_{T}(1-\varepsilon)\right]\frac{\partial T}{\partial t} = Q - \rho_{S}c_{S}A_{T}L_{T}\dot{V}\frac{\partial T}{\partial y} - u_{S}\left[T - T_{amb}\right] + k_{r}A_{T}\frac{\partial T}{\partial y} + h(T - T_{r})$$

$$(eq.2)$$

,where ρ_r (kgm⁻³) is the density and c_r (Jkg⁻¹K⁻¹) is the specific heat capacity of the granite pebbles, u_s (WK⁻¹) is the overall heat loss coefficient from the storage tank, k_r (Wm⁻¹K⁻¹) is the thermal conductivity of the granite pebbles and h (WK⁻¹) is the heat transfer coefficient from the oil to the pebbles.

The simulated packed bed used in this study was partitioned into 20 adjacent segments/sections. The new values of temperature of the HTF were obtained at the time step of 0.05 s. The temperatures generated by the model in this study were obtained basing on conditions considered for the experimental TES system. The initial conditions considered during the study are;

$$T(t=0) = T_r(t=0) = T_{amb} \cdot$$

The boundary conditions of the TES systems considered during the study are;
$$T(y=0) = T_{in} \cdot \frac{\partial T(y=H)}{\partial y} = 0 \cdot \frac{\partial T_r(y=0)}{\partial y} = \frac{\partial T_r(y=H)}{\partial y} = 0$$

, where y(m) is the axial coordinate and H (m) is the height of the tank. The level of accuracy between the experimental and the simulated results was analysed using percentage errors as; (Boylan & Syntetos, 2006);

$$\% \operatorname{error} = \frac{\left|A_{V} - E_{V}\right|}{E_{V}} \times 100\%$$

, where A_V is the approximate value and E_V is the exact value.

A number of parameters such as the void fraction, specific heat capacity and density among others were used during validation analysis. The thermo-physical parameters of the materials used for validation purposes are summarized in Tab. 1 and Tab. 2. Tab. 1 present the parameters of the materials used during validation. The density and specific heat capacity of Sunflower Oil in Table 1 varied with temperature (Mawire, 2016).

Property	Value
Volume of Sunflower Oil, V	7.0 ± 0.51
Specific heat capacity of pebbles, cr	$798 \pm 1 \text{ Jkg}^{-1}\text{K}^{-1}$
Density of pebbles, ρ_r	$2634 \pm 2 \text{ kgm}^{-3}$
Thermal conductivity of pebbles, k_r	$2.12\pm 0.02 \ Wm^{-1}K^{-1}$
Heat transfer coefficient from the oil to the pebbles, h	$120 \pm 1 \text{ WK}^{-1}$
Insulation value of the storage tank, u _s	$5\pm0.1~WK^{-1}$
Average ambient temperature, T _{amb}	23.0 ± 0.2 °C
Void fraction of small pebbles, ϵ	0.39 ± 0.01 (-)
Void fraction of big pebbles, ϵ	0.43 ± 0.01 (-)
Average diameter of small pebbles	$10.5 \pm 0.5 \text{ mm}$
Average diameter of big pebbles	$31.9 \pm 0.5 \text{ mm}$
Specific heat capacity of Sunflower Oil, c_s	c_s =2115.003+3.13T Jkg ⁻¹ K ⁻¹
Density of Sunflower Oil, ps	ρ _s =930.62-0.65T
Thermal conductivity, k _s	$k_s=0.161+0.018 \exp(-T/26.142)$

Tab. 1: Input parameters of materials used to model the TES system

Table 2 presents the parameters of the TES tank used in this study.

Tab. 2: Parameters of thermal	l energy storage system
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Property	Value	
Diameter of the tank	$0.123 \pm 0.005 \text{ m}$	
Insulation thickness	$0.056 \pm 0.005 \text{ m}$	
Height of bed	$0.692 \pm 0.005 \text{ m}$	

3. Results and discussion

3.1. Validation of model

The validation of the models for the Sunflower Oil only storage system, the Sunflower Oil/10.5 mm pebbles storage system and the Sunflower Oil/31.9 mm pebbles storage system at a flow rate of 4 mls⁻¹ is shown in Fig. 1. Experimental results presented by Lugolole et al. (2018) have been used for validation purposes. The temperature profiles at the top, middle and bottom sections of the experimental storage tank (Levels A, C, D) have been used for validation of the model. The inlet temperature is not presented since the focus is mainly on the temperature distribution inside the tank Generally, the experimental and simulated temperature profiles are close to each other for the same axial level considered as shown in Fig. 1. However, some discrepancies between the experimental and simulated temperature profiles are shown in Fig. 1. However, some discrepancies between the experimental and simulated temperature profiles are shown in Fig. 1. However, some discrepancies between the experimental and simulated temperature profiles are shown in Fig. 1. However, some discrepancies between the experimental and simulated temperature profiles are shown in Fig. 1. However, some discrepancies between the experimental and simulated temperature profiles are shown in Fig. 1. However, some discrepancies between the experimental and simulated temperature profiles are shown in Fig. 1. However, some discrepancies between the experimental and simulated temperature profiles are observed at different levels of the storage systems as shown

in Fig. 1. The experimental temperature profiles Te1 rise faster than the simulated temperature profiles Ts1 at level A of the tank in the first 30 mins for all TES systems in Fig. 1. This is because the temperature of the HTF entering the TES system initially rises faster due to the non-uniform and slightly higher heat flux at the outlet of the heater to the inlet of the storage tank in the experimental system. This makes the experimental temperature profiles Te1 to be higher than the simulated temperature profiles Ts1 at level A in all storages. However, the experimental temperature profiles Te2 and Te3 generally have lower temperature values in the initial stages of charging than the simulated temperature profiles Ts2 and Ts3 at level C and level D for the oil only storage tank. The reason is that the insulation of the storage tank is not uniform at the lower levels of the storage tank which results in more heat losses during the experiments. The model assumes uniform insulation of the storage system throughout the charging cycle. Similarly, the experimental temperature profiles Te2 and Te3 generally remain lower than the simulated temperature profiles Ts2 and Ts3 in the initial stages at level C and D for the small pebbles storage tank. The slower rise of the experimental temperature profiles is caused by the non-uniformity of the surfaces and sizes of the small pebbles. As a result, heat transfer between the small pebbles and oil is not uniform. Further, the void fraction is not uniform due to varying pebble sizes with an average diameter considered in the experiment, whereas the model assumes that all the surfaces and the particle sizes of the small pebbles are uniform. For the larger pebbles in Fig. 1 (c), the experimental and simulated temperature profiles are very close to each other in the initial stages at level C and D due to the large thermal mass of this storage system. Even though there are deviations between experiment and simulation, the total percentage deviation is not greater than 6 %, thus the model may be used with reasonable certainty to predict the behaviour of oil/packed bed systems.



Fig. 1: Validation for the three sensible heat storage systems at a flow rate of 4 mls⁻¹; (a): oil TES, (b): 10.5 mm pebbles TES and (c): 31.9 mm pebbles TES.

3.2. Effect of different flow rates

The simulation study of the Sunflower Oil/31.9 mm pebbles TES system is conducted at four different flow rates of 4 mls⁻¹, 10 mls⁻¹, 16 mls⁻¹ and 22 mls⁻¹, respectively, at a control input temperature of 200 °C, and simulation results are presented in Fig. 2. The temperature profiles of the experimental systems Levels A-D (top, lower top, middle and bottom) are simulated as Ts1-Ts4 as shown in Fig. 2. The Sunflower Oil/31.9 mm pebbles storage is used during simulation because of the larger thermal mass advantage of the larger pebbles. The temperature profile trends in Fig. 2 are observed to be different at the varying flow rates. Temperature profiles rise faster especially at the higher flow rates as compared to the lower flow rates due to the increase in the heat transfer rate. The thermal gradients are highest at the lowest flow rate of 4 mls⁻¹ as shown in Fig. 2 (a). The reason is that the heat from the preceding level in the simulation model takes a longer time to reach the next level due to the lower velocity of the HTF. As a result, the rate of temperature rise is low. Therefore, the lowest flow rate creates a high degree of thermal stratification within the TES system. This is in contrast to the profiles with the higher flow rates of 10 mls⁻¹ in Fig. 2 (b), 16 mls⁻¹ in Fig. 2 (c) and 22 mls⁻¹ in Fig. 2 (d) where the thermal gradients progressively decrease with increasing flow rate. The results further show that the decline in the thermal gradients is greater in Fig. 2 (c) and Fig. 2 (d) than with lower flow rates (Fig. 2 (a), (b)). This explains why the highest flow rate undergoes the highest de-stratification as shown in Fig. 2 (d). However, the rate of temperature rise is greatest at the highest flow rate of 22 mls^{-1} (Fig. 2 (d)) as compared to the lowest flow rate of 4 mls^{-1} (Fig. 2 (a)) due to the fastest heat transfer with the highest flow rate. Generally, the flow rate of 4 mls⁻¹ is chosen to be used in further simulations because it shows a better stratified distribution for the longest time for the four flow rates considered, which indicates a greater potential of storing more quality energy.



Fig. 2: Simulated TES temperature profiles for the Sunflower Oil/31.9 mm pebbles TES system at varying flow rates during charging; (a): 4 mls⁻¹, (b): 10 mls⁻¹, (c): 16 mls⁻¹ and (d): 22 mls⁻¹

3.3 Effect of varying TES input temperatures

Fig. 3 shows the simulated temperature profiles for the Sunflower Oil/31.9 mm pebbles packed bed at varying input temperatures during charging. The control heating input temperatures of 140 °C, 170 °C, 200 °C and 230 °C

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at the flow rate of 4 mls^{-1} are considered in the simulation. The selected medium range temperatures favour most cooking applications. Higher temperatures are not considered since they are not compatible to most pumps available in the markets as the pumps can be damaged due to high temperature heat. Consequently, replacement of pumps in the TES systems can make the technology expensive for cooking. Fig. 4 shows that the temperature profiles of all TES systems follow similar trends from the initial temperature of 20 °C to the highest temperature during charging. However, the difference is only observed in the highest temperature reached at the different control input temperatures. Fig. 3 (a) has the lowest maximum temperature of 140 °C due to the lowest control input temperature of 140 °C. A small amount of heat is dissipated to the TES system which makes the TES system to have the lowest rate of temperature rise at the control heating temperature of 140 °C. Lower temperatures are obtained within the period of 250 mins at the lowest input temperature. However, more energy is released to the TES system as the control input temperature increases as shown in plots (b), (c) and (d). The rate of temperature rise for plot (a) at the lowest input temperature is followed by plots (b, c, d) at the higher input temperatures respectively.



Fig. 3: Simulated TES temperature profiles for Sunflower Oil/31.9 mm pebbles TES at varying input temperatures: maximum (a) 140 °C, (b): 170 °C (c): 200 °C and (d): 230 °C control charging temperatures.

For example, the temperature achieved in plot (d) for the temperature profile T_{s1} at 100 mins is 220 °C which is greater than the temperature of 135 °C achieved in plot (a) in the same time. This explains why the highest maximum temperature of 230 °C is achieved with the highest set temperature (plot (d)) in 250 mins. Although the input temperature of 230 °C achieves the highest temperature as shown in Fig. 3, the input temperature used in the consequent simulations is 200 °C. This temperature conserves the thermal properties of the thermal oils which are used as the HTFs, and it is suitable for most domestic cooking applications.

3.4 Effect of different thermal oils (HTFs)

Fig. 4 shows the simulated temperature profiles for different thermal oils at the flow rate of 4 mls⁻¹ and at a control heating temperature of 200 °C. The four thermal oils considered are Sunflower Oil, Canola Oil, Olive Oil and Palm Oil. Each thermal oil used is assumed to have a volume of 7.0 l in the TES system. The volume of 7.0 l is selected since this is the volume of Sunflower Oil that was used during the experiments. Different thermal oils are studied to find out the effect of varying the densities and specific heat capacity values on the thermal oil (HTF) with better thermal properties for the TES system. The volume of (HTF) with better thermal oils are given in Table 3.

Thermal oil	Density (kgm ⁻³)	Specific Heat Capacity (Jkg ⁻¹ K ⁻¹)	Thermal conductivity (Wm ⁻¹ K ⁻¹)
Sunflower Oil	930	2115	0.161
Canola Oil	914	1910	0.188
Olive Oil	915	2300	0.170
Palm Oil	912	2400	0.172

Tab. 3: Properties	of thermal oils
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Out of the four storages in Fig. 4, Sunflower Oil TES (a) shows slightly larger thermal gradients up to the end of the charging cycle as compared to the other thermal oils. The explanation is that Sunflower Oil has the highest density among these four thermal oils considered. Similarly, the higher thermal capacity of Sunflower Oil also attributes to the slower temperature rise at all the axial sections of the storage tank such that the equilibrium temperature is achieved at a later time in comparison with the other thermal oils. As a result, the equilibrium temperature of 200 °C of the Sunflower Oil TES (a) is reached in the longest duration of 250 mins. Similar results of the Sunflower Oil TES were also found out in the study by Mawire et al., (2014). Fig. 4 (b) shows the fastest temperature rise such that the equilibrium temperature is reached at 200 mins before the other three storages. This is attributed to the lowest specific heat capacity value of $1910 \text{ Jkg}^{-1}\text{K}^{-1}$ of Canola Oil used in TES (b). The thermal responses in Fig. 4 (c) and Fig. 4 (d) are comparable. This is because the specific heat capacity of the Olive Oil TES system (c) and the Palm Oil TES system (d) are within the same range. The specific heat capacity of Olive Oil is 2300 Jkg⁻¹K⁻¹ while that of Palm Oil is 2400 Jkg⁻¹K⁻¹. Hence, the equilibrium temperature is reached around 230 mins for both TES (c) and TES (d). Generally, Sunflower Oil has better thermal stratification characteristics compared to the other thermal oils in this study and can be used as a suitable HTF for medium temperature packed bed TES systems. This is because Sunflower Oil TES maintains the biggest thermal gradients for the entire charging period of 300 mins as compared to the other three thermal oils considered. When the charging time is to be reduced, Canola Oil should be used since it shows the fastest rise to the thermal equilibrium. The densities of these two thermal oils are also almost identical making their thermal masses to be nearly the same.



Fig. 4: Simulated TES temperature profiles for different thermal oils; (a): Sunflower Oil, (b): Canola Oil, (c): Olive Oil and (d): Palm Oil.

3.5 Effect of different solid packed bed TES materials

Fig. 5 shows the temperature profiles of four sensible heat solid energy storage materials at a flow rate of 4 mls^{-1} and at a control input heating temperature of 200 °C. The sensible heat materials are granite pebbles, iron pebbles, alumina and sandstone pebbles. The selected solid thermal storage materials are assumed to have a spherical shape with an average diameter of 31.9 mm having a void fraction of 0.43 in the storage tank. Sunflower Oil is used as the HTF in the storage systems. The density, specific heat capacity and the thermal conductivity of solid packed bed TES materials are given in Table 4.

Material	Density (kgm ⁻³)	Specific Heat Capacity (Jkg ⁻¹ K ⁻¹)	Thermal conductivity (Wm ⁻¹ K ⁻¹)
Granite	2634	798	2.12
Iron	7860	462	79
Alumina	3905	765	30
Sandstone	2323	740	2.091

Table 4:	Properties	of solid	packed bec	1 TES	materials
Table II	1 Toper des	or some	pucheu bee		materiano

The results in Fig. 5 show that the Sunflower Oil/31.9 mm granite pebbles TES in Fig. 5(a) has the largest thermal gradients followed by the Sunflower Oil/sandstone pebbles TES in Fig. 5(d). This is because the granite pebbles and the sandstone pebbles have lower thermal conductivity values of about $2 \text{ Wm}^{-1}\text{K}^{-1}$ which causes the higher stratification. The Sunflower Oil/31.9 mm granite pebbles TES (a) has larger thermal gradients than the Sunflower Oil/sandstone pebbles TES (d) because the density of the granite pebbles is slightly higher than the density of sandstone pebbles. As a result, TES (a) has the slowest rise in temperature such that the equilibrium temperature is reached at 300 mins followed by TES (d) whose thermal equilibrium is observed at 250 mins.



Fig. 5: Simulated temperature profiles for different sensible heat solid energy storage materials; (a): 31.9 mm granite pebbles, (b): iron pebbles, (c): alumina pebbles and (d): sandstone pebbles.

Fig. 5(b) consisting of Sunflower Oil/iron pebbles shows the fastest rise in temperature and the smallest thermal gradients amongst the four storages. This is because the iron pebbles used in TES (b) have the highest thermal conductivity value of 79 $Wm^{-1}K^{-1}$. As a result, the Sunflower Oil/iron pebbles TES (b) attains the equilibrium temperature value at 200 mins earlier than the other TES systems. The temperature rise of the Sunflower Oil/iron pebbles TES in Fig. 5(b) is followed by the Sunflower Oil/alumina TES in Fig. 5(c). The Sunflower Oil/alumina TES (c) has a faster temperature rise as compared to the Sunflower Oil/granite pebbles TES and the Sunflower Oil/sandstone pebbles TES. This is because alumina has a thermal conductivity value of $30 \text{ Wm}^{-1}\text{K}^{-1}$ which is much greater as compared to the granite pebbles in Fig. 5(a), and the sandstone pebbles in Fig. 5(d) whose thermal conductivity values are very small (about 2 $Wm^{-1}K^{-1}$). This makes the Sunflower Oil/alumina TES to achieve the thermal equilibrium around 230 mins which is much earlier than TES (a) and TES (d). These results are similar to the study conducted by Mawire *et al.*, (2009) where the alumina storage system showed faster axial temperature rise than the fused silica storage because alumina has higher thermal conductivity compared to fused silica. Generally, the Sunflower Oil/granite pebbles TES in Fig. 5(a) has better thermal stratification characteristics than the other thermal storage materials. This is because this TES system has larger thermal gradients which imply less thermal mixing effects and lesser magnitudes of heat losses to the surroundings. Granite pebbles have other advantages of being readily available in most parts of the world. However, for faster charging of a packed bed TES system, higher thermal conductivity pebbles should be utilized.

4. Conclusion

A finite difference model for an oil/packed bed TES system was developed, and validated with experimental results. The results of simulation showed good agreement with the experimental results with an overall mean percentage error (deviation) of 6 % when using a flow rate of 4 mls⁻¹. This overall mean percentage error shows good agreement between the experimental and simulated results. The model was further used to simulate the effect of different flow rates, varying input temperatures, different thermal oils and different sensible heat solid energy

storage materials. An increase in the flow-rate led to the faster decrease in the temperature gradients in the TES systems considered. An inlet temperature increase resulted in faster rises of the storage tank temperatures, and higher maximum temperatures in the storage tanks. Considering the different thermal oils, the best storage performance was seen with Sunflower Oil since it showed better thermal stratification. The best packed bed sensible heat storage material was granite since it showed larger thermal gradients. The simulation study thus proved to be a useful tool in evaluating the thermal performance of different storage materials and should be used to complement rather than to completely substitute detailed experimentation. The simulation results can also be used by designers of solid-liquid TES systems to appropriately choose solid pebble bed materials based on their thermal performance. TES systems should be cheap if they are to be commercially viable (Herrmann & Kearney, 2002). For example, the price of Sunflower Oil is 1.20 USD per litre whereas gas costs 1.23 USD per litre. In terms of cooking applications, Sunflower Oil can be recycled (Lugolole *et al.*, 2018) whereas gas cannot (Dilip *et al.*, 2014). Hence, using a Sunflower Oil packed bed TES is a cheaper means of cooking in comparison with the other existing options (gas and electricity). The TES system modelled in this study is a cheap renewable energy resource for cooking purposes in homes.

5. Acknowledgments

The author would like to thank the National Research Funding (NRF) of South Africa for funds to carry out the research under the Incentive Funding for Rated Researchers (IFRR) scheme, Grant Number:127192. Reference: RA181002364433. I acknowledge that opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research are my, own, and that the NRF accepts no liability whatsoever in this regard.

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J-02. Sensible / Latent / Thermochemical Materials and Storage Concepts

Evaluation of the Cooling Process of Thermal Storage Tanks with LiNO₃-NaNO₃-KNO₃ Ternary Mixture as Working Fluid for CSP Plants

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Abstract

This research proposes the use of the mixture composed by 30%LiNO₃+57%KNO₃+13%NaNO₃ as thermal energy storage material in concentrated solar power plants due to its excellent thermal properties having a melting point of 127°C. The cooling process of the proposed ternary molten salt has been analyzed in a molten salt pilot plant built at the University of Antofagasta, which consists of a tank with a capacity of one ton, the controlled cooling tests were carried out from 400°C to 190°C. A computational fluid dynamics (CFD) model has been developed to analyze the transient cooling process of the molten salt tank, results were validated with the experimental data. The evolution of the temperature over time at all points in the tank has been obtained, the results show that the lowest temperatures are located near the free surface of the salts.

Keywords: Thermal Energy Storage; Lithium Nitrate; Concentrated Solar Power,

1. Introduction

Concentrating solar power, more commonly known as CSP, is unique among renewable energy generators because, although it is variable, like solar PV and wind, it can be easily coupled with thermal energy storage (TES) as well as conventional fuels, making it highly dispatchable (Kuravi et al., 2013). Concentrated solar power (CSP) technology with thermal energy storage (TES) can offer 24 h/day of operation at constant power (Wan et al., 2020), constituting an effective solution to the challenge of integrating renewable energy into the power system, as it provides renewable energy while bringing significant capacity, reliability and stability to the grid.

TES typically has lower capital costs than other storage technologies, as well as very high operational efficiency. The prototype TES system that was incorporated into the Solar Two project in Daggett, California, demonstrated a round-trip efficiency of over 97% (Pacheco et al., 2000), which was defined as the ratio of energy discharged to energy stored in the TES system. The thermal storage system of the above reference is a two-tank system designed to supply thermal energy at full steam generator output for three hours at the defined hot and cold salt temperatures of 565°C and 292°C, respectively (Kuravi et al., 2013). Two-tank molten salt thermal storage systems are considered the most mature thermal storage technology in solar thermal power plants (Zhang et al., 2020). In such system molten salts interact with the heat transfer fluid (HTF) of the solar field through a heat exchanger. During the day, the thermal energy from the solar field is used to maintain a steam turbine at full load and the rest of the solar field output is stored for later use. During cloud transients,

the storage is discharged to keep it at full load until the clouds disappear. When the sun sets, the storage is fully discharged to produce during night-time periods (Suárez et al., 2015).

The most commonly used energy stored material in thermal solar plants is a binary salt, called "solar salt" consisting of a mixture of 60% NaNO₃ and 40% KNO₃ (Gil et al., 2010). However, the relatively high melting point of this mixture (221°C) represents a significant risk of local solidification in the operation of solar power plants during standby periods, making solar thermal plants have to work at a minimum operating temperature of 292°C.

Lithium nitrate is one of the most promising additives in TES materials under study for application in CSP plants (Fernández, Galleguillos, et al., 2014). In the last years, different authors (Cabeza et al., 2015; Cáceres et al., 2016; Fernández, Ushak, et al., 2014; Ushak et al., 2015) have investigated the most important thermal properties regarding the use of LiNO₃ as TES material in CSP plants. Lithium based salts have been studied for thermal energy storage (TES) applications due to their excellent thermophysical properties. The addition of lithium nitrate is assumed to improve the performance of molten salts, extending the work temperature range. All existing research regarding the use of a ternary mixture is done on a laboratory scale, and there is no test on a larger pilot scale or higher. The ternary mixture containing 30%LiNO₃+57%KNO₃+13%NaNO₃ has excellent thermal properties by having a heat capacity of 21% over solar salt, and a crystallization temperature of 127 ± 5 °C so it is considered a viable alternative as a TES material (Henríquez et al., 2020).

In the present work, experimental tests of the cooling process of the ternary mixture 30wt% LiNO₃ + 57wt% KNO₃+13wt% NaNO₃ were carried out inside the tank of the pilot plant of molten sales of the University of Antofagasta. These tests served to know the process of crystallization, solidification, as well as the distribution of temperatures, and the times of the different processes. On the other hand, the experimental study is complemented by a computational fluid dynamics (CFD) model for a molten salt tank working with the ternary mixture as working fluid.

2. Experimental

The ternary mixture 30 wt%LiNO₃+57 wt%KNO₃+13 wt%NaNO₃ used in the pilot-scale plant tests were prepared with nitrates salts NaNO₃ (99.5%) and KNO₃ (99.5%) both provided by the company SQM, and LiNO₃ (99%) from Todini Chemical. The tests for the ternary mixture were carried out in a stainless-steel grade 316L tank of 0.83 m³ and 203 kg weight. The tank structure itself (1.2 m of internal diameter and 1.5 m of maximum height) is located over a refractory concrete base of 0.7 m thickness. Top and lateral walls of the tank are insulated with mineral wool (5 and 20 cm respectively) and the concrete base is insulated with foamglass (39 cm). The tank is partially filled with molten salt (34 cm of height), being the atmosphere air at ambient pressure. The tank was equipped with the commercial components detailed in Fig. 1, where four electric resistances of 1.2 kW provided the heat to melt the salt. The system contains 15 temperature sensors type PT100 class B 3-wire with 316-L stainless steel sheaths that are located inside and outside the tank. The sensors work in a temperature range of -200°C to 850°C (DIN 60751 specification) with an uncertainty of \pm (0.3 + 0.005T).

A GVSO40/160A high-temperature vertical pump recirculated the fluid at a rate of 1 m³ h⁻¹. The plant incorporates a piping heating system with electric tracing. In order to monitor and control the different variables of the heating process, the plant uses a data acquisition and communication system, consisting of two data loggers, and an integrated Unitronics V570 programmable logic controller (PLC).



Fig. 1: Molten salt pilot plant at the University of Antofagasta

3. Results

3.1. Cooling from 400 $^{\circ}$ C to 190 $^{\circ}$ C

Next, the cooling process of the ternary mixture of 30% LiNO₃+57% KNO₃ +13% NaNO₃ in the molten salt tank of the pilot plant described above is described. During the cooling process of the ternary mixture of 30% LiNO₃+13%NaNO₃+57%KNO₃ in liquid phase from 400°C to 190°C. The molten salt was held at 400°C for a period of 12 h. Subsequently, the electrical resistances are turned off and it is allowed to cool naturally to room temperature. Once 190 ° C is reached, the temperature is maintained for a period of 24 hours.

As the temperature decreases from 400°C to 190°C, all the sensors immersed in the ternary salt inside the tank, offer a descending linear behavior without heating, observing stratification.

3.2. Crystallization process of the ternary mixture

After cooling tests up to $190 \,^{\circ}$ C, the system was allowed to cool until the material crystallized inside the salt tank. In Fig. 2 it is possible to observe the ternary mixture in the liquid phase, at a temperature of $190 \,^{\circ}$ C. According to the image it is possible to clearly observe the suction of the pump, and the metallic duct of stainless-steel pipe in which the electrical resistance is inserted, completely immersed in the fluid, which in its liquid phase has an appearance transparent similar to that of water.



Fig. 2: Cooling of the ternary mixture with 30% LiNO3 + 57% KNO3 + 13% NaNO3 inside the tank at a temperature of 190°C.

At 127°C some crystallized areas are around the suction of the pump and the metallic duct of the electrical resistance.

4. Numerical method section

CFD calculations have been performed using commercial software ANSYS FLUENT[®] (Launder B. E. & B., 2013) to analyse the transient evolution of temperatures during a stand-by cooling period in a molten salt storage tank. The main objective of the CFD simulations was to obtain an estimation of crystallization time. Molten salt temperature distribution and the regions in which crystallization occur first for different scenarios was also analysed. In a first CFD model, the methodology is validated using the experimental data for the pilot-scale storage tank and simulation results of different molten salt types were compared. Subsequently, a second CFD model was developed for a state-of-the-art storage tank of CSP plants and simulation results of different molten salt types were compared.

4.1. Problem definition and experimental validation of the numerical method

In this section, a description of the developed CFD model of the pilot-scale storage tank including geometry, mesh and boundary and initial conditions is presented. Experimental molten salt temperature results of the transient cooling process are used for the validation of the developed numerical method.

4.2. Geometry, boundary and initial conditions and materials thermophysical properties

A sketch of the pilot-scale storage tank is shown in Fig. 3. Taking advantage of the axial symmetry, a 2D axissymmetric computational domain was adopted, obtaining a considerable reduction in terms of the mesh size and simulation time. The computational domain includes the molten salt (#1) and surrounding air (#2), mineral wool (#3) and foamglass (#4) insulations, a refractory concrete base (#5), a vertical pump (#6) located in the center-line of the tank and the stainless-steel tank structure (#7).



Fig. 3 – 2D axisymmetric pilot-scale tank computational domain and boundary conditions

The electrical resistances, which are off during the cooling process, are not considered in the computational domain.

The considered boundary conditions (BC's) of the problem were:

- (i) axisymmetric BC in the tank centerline,
- (ii) convective and radiative heat transfer BC at lateral and top walls in contact with exterior air at a constant temperature of 15°C. External radiation effect is included in the selected value of the convective heat transfer coefficient h of 10 W/m²K.
- (iii) thermal resistance parameter with fixed temperature BC in the foamglass bottom to include the thermal insulation effect of the ground underneath the foamglass layer. This additional ground layer thermal resistance is computed as $\Delta y/k$ where Δy is the ground thickness and k is the ground thermal conductivity. A representative deep-ground constant temperature equal to the annual average temperature was specified at the outside wall surface. A sandy ground of 10 m thickness with a constant thermal conductivity of 2 W/mK was considered, with an external temperature of 15 °C, representative for the annual average temperature of Antofagasta (Chile).

Materials initial temperatures were set according to the experimental data, starting with a molten salt temperature of 400 °C. The rest of the initial temperatures were: stainless steel 385 °C, rock wool 240 °C, foamglass 165 °C and concrete 360 °C.

Materials thermophysical properties are summarized in tables 1 and 2 as a function of temperature for solids and fluids respectively.

Tab. 1: Temperature	e dependent thermop	hysical properties	(solids). Property= อ	$\mathbf{a}_0 + \mathbf{a}_1 \cdot \mathbf{T} + \mathbf{a}_2 \cdot \mathbf{T}^2 + \mathbf{a}_2 \cdot \mathbf{T}^2$	a ₃ ·T ³ , T(°C)

Material	ρ (kg·m ⁻³)	$Cp (J \cdot kg^{-1} \cdot K^{-1})$	$\lambda (W \cdot m^{-1} \cdot K^{-1})$
Mineral wool	a ₀ = 20	$a_0 = 871$	$a_0 = 3.49 \cdot 10^{-2}, a_1 = 9.62 \cdot 10^{-5},$

			$a_2 = 1.47 \cdot 10^{-7}, a_3 = 4.21 \cdot 10^{-10}$
Foam glass	$a_0 = 20$	$a_0 = 871$	$a_0 = 3.76 \cdot 10^{-2}, a_1 = 2.53 \cdot 10^{-4},$
			$a_2 = -3.29 \cdot 10^{-7}, a_3 = 6.75 \cdot 10^{-10}$
Concrete	$a_0 = 2250$	$a_0 = 750, a_1 = 0.75$	$a_0 = 1.70$
AISI 316	a ₀ = 7918	$a_0 = 544$	a ₀ = 16.3
Air	$a_0 = 1.18$,	$a_0 = 1006$	$a_0 = 1.52 \cdot 10^{-5}, a_1 = 8.49 \cdot 10^{-8}$
	$a_1 = -2.65 \cdot 10^{-3}$		$a_2 = -2.18 \cdot 10^{-10}, a_3 = 2.85 \cdot 10^{-13}$
	$a_2 = 2.50 \cdot 10^{-6},$		

Tab 2. Temperature dependent thermophysical properties (fluids). Property= a₀ + a₁·T + a₂·T² + a₃·T³, T (°C)

Material	ρ (kg·m ⁻³)	Cp (J·kg ⁻ ¹ ·K ⁻¹)	$\mu \left(kg \cdot m^{-1} s^{-1} \right)$	$\lambda (W \cdot m^{-1} \cdot K^{-1})$
Solar salt	$a_0 = 2090,$ $a_1 = -0.64$	$a_0 = 1443,$ $a_1 = -0.17$	$a_0 = 5.50 \cdot 10^{-2}, a_1 = -4.35 \cdot 10^{-4}$ $a_2 = 1.22 \cdot 10^{-6}, a_3 = -1.16 \cdot 10^{-9}$	$a_0 = 0.45$
Ternary salt	$a_0 = 1803,$ $a_1 = -0.50$	a ₀ = 1409	$a_0 = 8.00 \cdot 10^{-2}$	a ₀ = 0.55

4.3. Experimental validation

A validation of the numerical approach was performed by comparing the numerical predictions against the previously reported experimental results during the novel ternary molten salt cooling down. Experimental results were measured from an initial molten salt temperature of 400 °C until a final secure operation limit temperature of the molten salt defined at 190 °C. The variables compared in the validation are the transient temperature evolution of thermocouples located in the molten salt (sensor #6), interface wall tank-insulation (sensor #15), and interface bottom tank-concrete (sensor #11). Crystallization time is also a parameter of interest in the validation.

Validation results are shown in Fig. 4, including with dashed line the crystallization temperature of the molten salt (127 °C) and an upper secure operation temperature limit (190 °C). Results show a similar trend between the experimental and the simulated results for sensors #6, #11 and #15 with percentual temperature relative differences below 1.5 % in average and 4 % in the worst case. Higher temperature differences between the experimental results and the simulations were found during the initial time periods, due to the fact that initial temperature conditions are only known in a few points of the computational domain, being the rest of temperatures assumed. Simulation results also predict accurately the time in which the molten salt reach the temperature limit of 190 °C, 70.9 h, in comparison with the experimental value of 71.8 h. Taking the temperature



limit as the reference, simulations prognosticated an extra period of 54.5 h before crystallization materialize at 127 °C.

Fig. 4. Simulated results vs experimental results in the cooling down of the novel ternary molten salt.

5. Conclusions

The present work carried out at laboratory scale and in the pilot, plant confirms the excellent thermophysical properties that would allow Chilean lithium nitrate to be an option to replace the current solar salt, with a stable minimum operation temperature around 190 °C.

CFD model of the pilot-scale tank was developed and validated with the experimental results in terms of the ternary mixture salt temperature evolution.

Percentual temperature relative differences were below 1.5 % in average and 4 % in the worst case.

The time elapsed experimentally of the ternary mixture cooling process from 400 to 190 °C was 71.8 h, in good agreement with 70.9 h obtained with CFD simulations.

6. Acknowledgements

The authors would like to acknowledge the financial support provided by CONICYT / FONDAP 15110019 "Solar Energy Research Center" SERC-Chile. FIC-R 30413089 – 30488809 funded by Antofagasta Government. Scaling-UP Engineering 2030 UA-OTL Funds. VIU21P0051 Project National Research and Development Agency, Government of Chile

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Experimental Study on the Performance of an Advanced Integral Collector Storage System with Two Types of Phase Change Material Composites

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Abstract

Integral Collector Storage (ICS) systems, combine a water storage tank and a solar collector into one single unit. The technology is very promising, however one of its major drawbacks is heat loss during collection and storage of solar energy. The issue can be addressed by integrating ICS technology with phase changing materials, which have potential to absorb a large amount of heat during the phase transition and therefore minimize temperature fluctuations. However due to the low thermal conductivity of the PCMs and their susceptibility to leakages, their application to ICS is limited. In this work, two different PCM materials with expanded graphite and advanced system structure, were studied in terms of improving ICS performance for residential applications.

Keywords: phase change materials, integral collector storage, flat plate solar collector, expanded graphite

1. Introduction

Solar radiation is one of the major renewable sources of energy in today's world. Solar energy can be captured through a flat plate solar thermal collector. The working principle of a flat plate thermal panel is collecting the solar radiation as it passes through a transparent layer and is drawn by the absorber plate.

The absorbed radiation is then transferred to a medium (e.g. water or air circulating in the tubes) to increase its temperature. The collector housing and the underside of the absorber are insulated in order to minimize the conduction losses (Dabiri, 2016). Typical output temperatures of a flat plate solar collector range between 40° C and 60° C which is most suitable for domestic applications.

As demonstrated by (Kessentini et al., 2011) the major problem with the flat plate solar collector which needs to be addressed, is heat loss from the absorber to the ambient environment. One of the ways to prevent heat losses in the absorber plate is combining it with thermal energy storage (TES).

TES is a technology which allows for accumulation of thermal energy, by heating a storage medium and utilizing the stored energy later. The advantages of using thermal energy storage in renewable energy systems are: 1) an increase in the system's efficiency and reliability; 2) a reduction in the running costs; 3) better pay back periods and a reduction in CO_2 emissions (Dincer Ibrahim & Rosen A. Marc, 2011).

One of the most promising thermal energy storage methods for renewable technologies are phase change materials, which because of their high energy storage capacity became a very potent thermal energy storage system (Whiffen & Riffat, 2013). PCMs are proving to be a good option to economically achieve energy efficiency in buildings (Iten et al., 2016). Phase change materials allow to store large amounts of heat per unit volume during their phase transitions, one of the biggest issues on the way to successfully utilize PCMs as thermal energy storage, is their low thermal conductivity, one of the ways of tackling this issue is mixing PCMs with expanded graphite which provides the composite with good level of heat conductance (Alzoubi, 2015), (Li et al., 2019). PCM/EG composites are very attractive in terms of energy storage capacities and thermal management because of their heat storage characteristics and high thermal conductivity. The use of a composite has a potential to reduce the weight of the thermal storage unit (Zhang & Fang, 2006). Paraffins are ideal to create composites with expanded graphite, because of their safety, high latent heat, non-corrosiveness and stable chemical properties (Shi et al., 2015).

2. Materials and methodology

2.1 Preparation of a test rig

In order to provide a reference to assess the performance of the developed ICT-PCM system a panel without phase change materials has been tested under lab conditions. The model of the tested solar thermal collector was FKF 200H Al/Cu connected to a coil of a 160l water storage tank, expansion vessel, three speed circulating pumps, a flow meter and a data logger with thermocouples. The solar thermal collector was positioned vertically on a frame, in order to imitate its integration with the front face of a building.



Fig.1: Schematics of a solar thermal system operation

Fig.2: Solar thermal system on a test rig

Because of the unpredictable outdoors conditions the assembled system was placed and tested indoors under a solar simulator which can provide light intensity of up to 1200 Wm² (fig.3).

The average irradiation measured with a pyranometer, reaching the front surface of the tested panel ranged between $330 - 360 \text{ W/m}^2$ which can be approximated to a moderate, partially sunny day in the UK and the average water flow rate during the active operation of the system was in the region of 31 / minute.

The testing methodology involved two steps: 1.) warming and passive cooling of the studied panels. During this stage the panels were warmed up both passively (without water circulation) and actively (with the circulating pump switched on). After the simulator was switched off the panels were left to cool down. This test allowed for an initial observation of the heat retrieving potential of the PCM-EG composites.

After the initial stage of the experiment, it was decided to replace the A28/EG composite with an A36/EG, as phase change materials with higher melting points retain heat at higher temperatures which is more suitable for the TES system.

2.) The second step involved testing the amount of heat stored in the PCM composites. It involved passive and active charging of the reference and hybrid PCM panels and then retrieving the stored heat into the water tank. A two-way circulating system explained in chapter (2.4) was developed for the purpose of this test.

The reason for creating the bypass circulation system was the fact that the hybrid ICS – PCM/EG system was converted from the solar thermal panel and it remained with the potential to actively warm up the water inside the tank with open water circulation inside the tanks coil. The focus of this study however was only on the amount of heat which could be stored and retrieved from the collector's thermal energy storage system, and thus bypass circulation was created which allowed to omit the tanks coil during the charging phase of the ICS-PCM/EG panel and then retrieving the stored heat into the tank after switching off the solar simulator.

2.2 Fabrication of the ICS - PCM system

The ICS-PCM system fig. 4 was fabricated for the experimental testing under same test rig and conditions as the reference panel.



Fig.4: Schematics of a solar collector with PCM/EG

Two types of phase change material composites have been structured and integrated into the solar collector, in close contact with its absorber plate and collector pipes.

2.3. Preparation of the PCM-EG composite

The process of making a composite involved crushing solid PCM material, consisting of 1kg of expanded graphite and 3kg of phase change materials, which were both melted together and stirred until uniformity and placed inside an aluminum bag (fig.5).



(a)

(b)



Fig. 5: Preparation of a PCM-EG composite: (a) Crushing solid PCM material (b) Pouring graphite into a mixture (c) Stirring until uniformity (d) Placing the composite inside an aluminum bag

Phase change materials used in the experiment were PlusICE organic A28 and A36 with the properties seen in a table1.

PCM type	Phase change temperature (°C)	Density (kg/m³)	Latent Heat Capacity (kJ/kg)	Volumetric Heat Capacity (MJ/m ³)	Specific Heat Capacity (kJ/kgK)	Thermal Conductivity (W/mK)
A28	28	789	265	209	2.22	0.21
A 36	36	776	250	194	2.3	0.22

Tab. 1: Properties of A28 and A36 PCMs

The thermal conductivity enhancer used in the study was the SIGRATHERM GFG 600 highly conductive expanded graphite, which was mixed with the PCM material in a 1:3 ratio. Altogether 20 kg of the PCM/EG composite have been prepared and placed in the back of the collector. Below are the pictures made with a scanning electron microscope, figure 6(a) show that expanded graphite has a porous structure which creates a large absorptive area on its surface, BET surface area of EG used in this study is 20 m²/g. Expanded graphite composites with A28 PCM material fig. 6 (b) appear more smooth and uniform in structure than the EG-A36 composite fig. 6 (c).



Fig. 6: SEM pictures of pure expanded graphite (a) (Shi et al., 2015), A28 (b), A36 (c) PCM/EG composites

2.4. Incorporating PCM/EG composite into a panel

After the PCM/EG composite was prepared and encapsulated in aluminum bags it was then inserted into the back of a panel and then secured with a Quinn Therm insulation and an aluminum cover sheet (fig.7).



Fig 7: Preparing encapsulated PCM/EG in the back of the panel: (a) heat exchanger with absorber plate (b) encapsulated PCM/EG composites (c) PCM/EG composites covered with Quinn Therm insulation (d) back of the panel covered with an aluminum sheet

2.5. The production of a two-way circulation system

The next stage of the experiment involved producing a two-way circulating system which allowed for water circulation in 2 modes (fig.8).

During the first mode valve 1 is shut and valve 2 is open, this allowed water to circulate inside the panels' heat exchanger, while bypassing the coil of the tank. During this phase the panel was absorbing heat from the solar simulator.



Fig 8: Schematics of a two - way circulation system

During the second mode of the operation, valve 1 was opened and valve 2 was shut which allowed to recover heat stored inside the panel to the water tank. This two-mode operation system enabled the comparison of the amount of heat stored in the panel with and without phase change material composites.

3. Results and analysis

During the first stages of the experiment, a reference panel and a panel with PCM/EG A28 and A36 were tested. The temperature inside the panels was measured on the panels' inlet and outlet.

After being heated, the reference panel cooled down from 44° C to 15° C in 3 hours with an average temperature during the cooling period of 23.15°C. The panel shown a very low heat retention properties because apart from the heat stored in water and piping of the panel, there are no other heat retention mechanisms.



Fig 9: Reference Non – PCM panel warming + cooling

Results obtained from testing the hybrid PCM panel with A28/EG composite show that after the warming period it cooled down passively from 35°C to 19°C in 11 hours with an average temperature during the cooling period of 21.28°C (fig.10).



Fig10: PCM panel with A28/EG warming + cooling

The PCM/EG – A36 panel shows a much lower internal heat loss than the reference panel. It took 12 hours and 45 minutes for it to cool down from 42°C to 20°C, with an average temperature during the cooling process of 24.54 °C (fig.11)



Fig 11: PCM/EG – A36 panel warming + cooling

3.1 Heat retrieving from a PCM and non PCM panel's

During the next phase of the experiment, results from a charging and discharging panel with a two-way operating cycle were obtained (fig.12). Temperature readings were taken from inside the panel's sensor and from within the tank.



Fig 12 : Heat retrieving: (a) non – PCM reference panel (b) PCM panel

The non PCM panel charged in 60 minutes from 22°C to 67°C whereas the PCM panel was charged in 5 hours 54 minutes from 16°C to 65 °C indicating that PCM materials were absorbing heat for extended period. During the heat retrieving stage, 8.5° C was recovered from the PCM/EG – A36 panel into the tank, and 3.5° C of heat was retrieved from the non PCM panel.

3.2. Calculating the amount of heat retrieved from the PCM and non PCM panels

The amount of heat retrieved into the tank from both panels can be calculated with following equations:

$$Q = \rho V C_p (T_f - T_i)$$
 (eq. 1)

$$V_{tank} = \frac{\pi}{4} D^2 H \tag{eq. 2}$$

where:

 $\rho_{water} = 997 \frac{kg}{m}^{3}$ $C_{pwater} = 4.2 k J/kgK$

Therefore:

 $Q_{PCM/EGpanel} = 5151 \, kJ$ $Q_{reference panel} = 2121 \, kJ$

The quantity of heat energy stored in the PCM materials is the difference between heat retrieved from the hybrid PCM panel minus the heat recovered from a reference panel.

Hence: $Q_{PCM} = 5151 \text{ kJ} - 2121 \text{ kJ} = 3030 \text{ kJ} = 0.842 \text{ kWh}$

4. Economic and environmental importance

The amount of heat retrieved from the PCMs into the tank after one charging cycle was calculated as (0.842 kWh). If we assume two daily charging and discharging cycles of the PCM-EG panel, it has the potential to reduce the annual cost of water heating by £96 and the CO₂ emissions could be reduced by 141 kg. Although this is a promising initial result, future studies need to focus on increasing the performance of the ICS – PCM/EG system in order to make the technology more sustainable and cost effective.

5. Conclusions

In this study the potential of using the phase change material composites for integral collector storage systems has been investigated. The panels with PCM/EG – A28 and A36 were demonstrated to cool down 8 and 9 hours longer than the reference panel respectively. The amount of heat retrieved to a PCM/EG – A36 panel was 8.5° C as opposing to a 3.5° C retrieved to a tank from a panel without phase change materials.

These results show that PCMs have good potential for heat retention inside the studied hybrid PCM/EG panel and could thus play a major role in increasing the efficiency of an ICS system. Furthermore, it could also address issues faced by the conventional ICS system. Further research in this topic is needed and it should focus on the ways of further increasing the thermal capacity of PCM/EG energy storage e.g. through increasing the amount of PCMs inside the collector. Future work on the system should also involve optimizing the system with phase

change materials at higher melting points. The system should also be tested under various types of outdoors climatic conditions.

6. Acknowledgments

I would like to thank DEF, EPSRC CCB (EP/V011340/1) and H2020 IDEAS (Grant no.815271) programs for supporting this research, to Ulster University lab technicians Philip Dalzell and Shane Smyth for their help with assembling the test rig and to Dr Bruno Alessi for taking the pictures of the PCM – EG composites with the SEM microscope.

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J-03. Long-term and Short-term Storage
A Technical Introduction of Water Pit for Long-term Seasonal Solar Thermal Energy Storage

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Abstract

The total amount of solar energy resources is abundant, clean and widely distributed, but there are also problems such as low energy density, discontinuity and large seasonal difference of radiation amount. Water pit for seasonal solar thermal energy storage is one of the important technical routes to realize "winter uses stored solar heat from summer" and "zero carbon heating." It can effectively solve the mismatch of solar energy supply and demand in time and space, and it is a crucial technology to solve the problem that solar energy cannot be continuously utilized. The key idea of this technology is to store the solar energy collected in non-heating seasons in the water pit for spacing heating in winter. On the one hand, this technology solves the idle problem of solar collector in non-heating season; on the other hand, it can realize all-weather heating under complicated weather conditions, thus achieving a high guarantee rate of solar energy. This paper introduces the basic principle, application cases and cost analysis of water pit for seasonal heat storage, and analyzes the main problems and future research directions. This paper mainly introduces the related technologies of the 3000 m³ water pit long-term seasonal solar thermal energy storage system in Huangdicheng town, China.

Keywords: Solar energy, Seasonal thermal storage, Water pit of heat storage

1. Introduction

The total amount of solar energy resources is abundant, clean and widely distributed, but there are also problems such as low energy density, discontinuity and large seasonal difference of radiation amount. Allegrini J. et al. (2015) pointed out that the most significant mismatch is between the solar heat availability in summer and the high space heating demand in districts during the winter season. The variation trend of solar radiation, demand for heat, demand for cold and demand for domestic hot water in many typical heating areas over time is shown in Fig.1. The total amount of solar radiation changes in a single peak pattern throughout the year. In summer, solar energy resources are abundant but often cannot be utilized effectively, while in winter, solar energy resources are scarce and in great demand. In daily life, the demand for domestic hot water is generally stable, and the demand for domestic hot water in summer and autumn. The main contradiction between the distribution of solar energy resources and the demand for heat is that residents have a strong demand for heat in winter, but the solar radiation in winter is at the peak of the whole year.

In this background, SPEYER E. (1959) and Buscheck T. A. et al. (1983) have put forward the concept of seasonal thermal energy storage (STES) that can bridge the gap of intermittency in solar energy. When the "source" side (solar heat source side) and the "load" side (energy using side) have the significant seasonal characteristic, STES can effectively solve the mismatching characteristic of the solar energy heating system in time, space and strength. Therefore STES can transfer the solar heat from the summer or transition seasons to the winter, and expand the depth and breadth of solar heat utilization. While this concept, seasonal thermal energy storage, a long-term storage system, is well known for its long storage periods that last up to several months (Guo F et al., 2017). Sweden took the lead in the research of large-scale STES in the 1980s (Ochs F. et al, 2009), and now many countries have built relevant application systems with STES (Bauer D. et al. 2010; Dahash A. et al. 2019; Fong M. et al. 2019; Rad F. M. et al. 2017; Zhou X et al. 2020). In addition, STES can provide 50%-100% solar

guarantee rate (Hennessy J. et al. 2019; Xu J et al. 2019).

Thermal energy storage(TES) technology can be divided into sensible TES, latent TES and chemical TES according to different types and mechanisms of thermal storage (Xu J et al. 2019). Whether it is latent TES technology or chemical TES technology still in the stage of laboratory research, its application in cross STES is not mature (Li X et al. 2014). At present, sensible TES is most widely used in STES (Pinel P. et al. 2011). Sensible TES technology mainly includes borehole thermal energy storage(BTES) technology, aquifer thermal energy storage(ATES) technology, tank thermal energy storage(TTES) technology and pit thermal energy storage(PTES) technology, as shown in Fig.2. TTES technology is relatively simple and mature, which uses a large layered water tank to store hot water. PTES technology also uses a large container to store heat. The difference is that PTES technology generally stores hot water in underground containers, as shown in Fig. 2 (d). In a sense, the TTES technology is similar to the PTES technology. It should be noted that the TTES technology described in this paper specifically refers to the free stand water tank thermal energy storage technology above the ground, and the underground buried water tank thermal energy storage technology belongs to the PTES technology. The construction of water pit is generally divided into two types: one is the concrete water tank buried underground or semi underground built by reinforced concrete, also named as underground water tank thermal energy storage technology. And the other is a storage container formed by directly excavating a water pit on the ground and special treatment of the side wall and bottom, which often adopts a floating roof. The cost of the latter TES technology is significantly lower than that of the first underground water tank (Dahash A. et al. 2019), because in essence, the first underground buried water tank TES technology still belongs to TTES. There are two kinds of water pit thermal energy storage media: one is hot water, the other is the mixture of gravel (or sand) and water, which is called gravel-water TES technology (Marx R. et al. 2009; Ochs F. et al. 2008). Since the heat capacity of the gravel-water is lower than that of the single hot water, the volume required for heat storage of gravel-water is about 50% higher than that of the single hot water in order to achieve the same thermal storage (Bai Y et al. 2019; Hesaraki A. et al. 2015; Novo A. V. et al. 2010;).



Fig. 1: Annual variation trend of solar radiation and demand for heat (cold) in typical heating areas

Fig. 2: Four types of seasonal sensible thermal energy storage

Whereas Table 1 compares the four types of STES in terms of TES medium, TES density, the equivalent TES volume, performance parameters, characteristic requirements and system cost (Argiriou A. A. 1997; Dahash A. et al. 2019; Novo A. V. et al. 2010; Sibbitt, B. et al. 2015; Pinel P. et al. 2011; Xu J et al. 2014; Zhao X et al. 2017). Then, the TES density of TTES is the highest, followed by PTES, and the BTES is the lowest. BTES and PTES have high requirements for local geology. The cost of TTES is the highest, and BTES is the lowest. In general, water pit thermal energy storage system is currently the most reliable and widely used system for STES at present (Novo A. V. et al. 2010; Pinel P. et al. 2011).

Many countries in the world have carried out research on the water pit for long-term STES and built some application projects. For example, Chemnitz District Heating project of Germany, Denmark's Marstal PTES, and

so on (Fan J et al. 2017; Mangold D. et al. 2004). Asia is rich in solar energy resources, but there are relatively few projects of STES. And the STES technology is in the development stage in Asia at present. China has established some demonstration small-scale STES projects, and is actively developing large-scale, long-term, low heat loss and low-cost STES technologies (Huang J et al. 2019; Tao T et al. 2019; Xu L et al. 2018; Xiao W et al. 2010). This paper mainly introduces the related technologies of the 3000 m³ water pit long-term seasonal solar thermal energy storage system in Fanshan Town, Zhuolu County, Zhangjiakou City, Hebei Province, China(40° 13′ 18″ N,115° 26′ 6″ E).

TES type	TES medium	TES density / (kW • h/m ³)	Equivalent TES volume(Re lative to 1 m ³ water)/m ³	Burial depth (m)	Characteristic requirements	Overall cost
TTES	Water	60~80	1	 (a). Can be built on the ground [24]. (b). Underground 5~15 	(a). High requirements for thermal insulation technology when on the ground [24];(b). Relatively stable ground conditions are required when buried underground.	Highest
PTES	Gravel (Sand)- water/Water	30~50	2~3	5~15	(a). stable ground condition.(b). No ground water flow is preferred.	Higher
ATES	Gravel (Sand)/Water	30~40	2~3	20~50	 (a). Stable ground condition. (b). Natural aquifers with high permeability. (c). There is a clear boundary between the top and bottom of the aquifer. (d).No or low natural ground water flow. 	
BTES	Water/Soil	15~30	3~5	(a). Stable ground condition (b). Easy drilling construction 30~100 (c). The heat capacity and ther conductivity of soil are large (d). No or low natural ground wate		Low

Tab. 1: Comparison of characteristic of four types of sensible thermal energy storage (Argiriou A. A. 1997; Dahash A. et al. 2019;
Novo A. V. et al. 2010; Sibbitt, B. et al. 2015; Pinel P. et al. 2011; Xu J et al. 2014; Zhao X et al. 2017)

2. Profile of the long-term PTES demonstration Project in Huangdicheng town

The long-term PTES demonstration project in Huangdicheng town was designed by the Institute of Electrical Engineering, Chinese Academy of Sciences, and Dahua Group was responsibled for the auxiliary design of buildings and system pipelines, providing 3000 ~ 5000m² building heating for Dahua Jianguo Hotel. The construction of the project began in April 2017 and has been put into operation since April 2018. The design objective of the system is realize the efficient thermal collection and storage of solar energy in the heat storage season. In the heating season, it realizes the efficient collection of solar energy and the efficient heat extraction of water pit for thermal storage, completes the central heating of energy-saving buildings of 3000 m², and solves the problems of low solar energy utilization rate and the imbalance of heat supply and demand between summer and winter in the traditional solar central heating system. The system can collect and store solar energy throughout the whole year to meet the heating needs of the hotel during the heating season (Bai Y et al. 2019).

The system consists of three subsystems: solar tower thermal collection system, seasonal thermal storage system and heating system, as shown in Fig. 3. Basic operating principle of the system: in the non-heating season, the circulating pump of the solar tower thermal collection system pumps water from the bottom of the cylindrical thermal storage water pit, and after passing through the solar tower thermal collection system, the abundant solar energy in the non-heating season is converted into thermal energy, which is returned from the upper part of the thermal storage water pit, and the cycle repeats until the water temperature reaches the design temperature. During the heating season, the control system pumps hot water from the upper outlet of the thermal storage water pit to provide heat to the heating user. The density of water is relevant to temperature. In the long-term heat storage process, water will have temperature stratification due to the action of buoyancy, resulting in the phenomenon of high upper temperature and low lower temperature. A good temperature gradient is not only conducive to improve the operation efficiency of the heat collection system, but also an important measure to improve the heat storage efficiency, because the destruction of temperature stratification will enhance the mixing of cold and hot fluids in the water pit and reduce the heat storage effect of the thermal storage water pit.



Fig. 3: The long-term water pit thermal storage/heating system in Huangdicheng town

2.1. Solar tower thermal collection system

The system is mainly composed of heliostat field, tower heat receiver, pipe network and other components, reflecting the advantages of high thermal collection temperature, high light concentration ratio, large capacity and so on.

The heliostat field of the system has a total daylighting area of $739m^2$ which is composed of 66 small heliostats with a single daylighting area of $11.2m^2$. Each heliostat is assembled by four unit mirrors with a size of 1700mm × 1640 mm, the heliostat surface is a 4 mm ultra white float glass silver plated mirror with reflectivity $\ge 93\%$. The tubular receiver is composed of 88 vertical Q235 steel pipes, which are welded on the upper and lower headers, and the surface is coated with Pyromark1200 high temperature coating. The heliostat field focuses the sunlight reflection on the surface of the tubular receiver, and the water is heated from the inlet header at the lower end of the heat collector to the outlet header at the top. The tubular receiver is the core component that converts radiant energy into thermal energy, and its relevant structural parameters are shown in Table 2.

Tab. 2	2: The	structural	parameters	of	tubular	receiver
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Parameters	Numerical value
Number of receiver tubes N_t	88
Outer diameter of receiver tubes D _o	25mm
Inner diameter of receiver tubes D _i	20mm
Surface coating emissivity of receiver tubes ε	0.87
Surface coating absorption of receiver tubes α	0.9
Height of daylighting opening of receiver H	1.7m
Width of daylighting opening of receiver W	2.8m
Thermal conductivity of receiver tubes λ	50W/(m•K)

2.2. The system of seasonal thermal storage

The system of seasonal thermal storage includes 3000m³ water pit thermal storage, supporting equipment and relevant sensors, as shown in Fig. 4 and Fig. 5. The cylindrical water pit is poured by concrete, the concrete wall is 0.3m thick, the underground burial depth is 1m, and the top cover of the water pit is covered with 0.2m thick polystyrene extruded insulation board. Relevant physical parameters are shown in Table 3.



Fig. 4: 3000m³ water pit of seasonal thermal storage

Fig. 5: The temperature sensor layout diagram of water pit thermal storage

Material	Density (kg • m ⁻³)	Thermal conductivity (W • m ⁻¹ • K ⁻¹)	Thermal capacity (J•kg ⁻¹ •K ⁻¹)
Soil	900	1.3	2500
Concrete	2500	1.28	970
Polystyrene extruded insulation board	28	0.042	1500
Water	1000	0.642	4200

Tab. 3: Material physical parameters

2.3. Pipe network and other components

Pipe network, water pump, heat exchanger and other equipment are not highlighted. And there is a buffer tank in the system. The buffer tank is a vertical stainless steel tank with a structural size of $4 \text{ m} \times 4 \text{ m} \times 3 \text{ m}$ (length \times wide \times High), with a volume of 48 m^3 . The buffer water tank can not only achieve short-term thermal storage, but also play the role of heat buffer and stable working conditions between the heat collection system and the heat load. Therefore, it plays an important role in the whole seasonal storage/heating system.

It should be noted that the first phase of the seasonal thermal storage/heating system is designed to provide heat for the building with a heating area of 3000 m^2 , and then to increase to the hotel with a construction area of 18044.4 m^2 and the hotel apartment with a construction area of 19379.8 m^2 . It is also equipped with 2t gas-fired boiler and 1080 kWh electric boiler.

3. System operation mode and control strategy

The system sets up four operation modes and three control strategies considering the actual needs and system design characteristics.

3.1. System operation mode

The operation of the seasonal thermal storage system is designed into two stages: thermal storage season and heating season from the perspective of energy source and transfer according to different functional objectives due to the inevitable unstable and discontinuous characteristics of solar radiation and the time-varying energy demand of heat users. The operation mode of each phase is described as follows:

Mode 1: Thermal storage season - thermal storage mode of water pit

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The softened water at the bottom of water pit is heated by circulating pump and solar tower thermal collection system, and then filled into the upper part of the water pit in the thermal storage season. The temperature stratification is gradually formed inside the water pit. At the same time, the soil around the water pit is gradually heated, and the temperature of the upper layer of the water pit finally reaches $80 \sim 95$ °C, as shown in Fig. 6(a). According to the actual heat demand of users and scientific research demand, two common operation control modes are designed for the heat collection system: temperature control operation control and continuous operation control.

Mode 2: Thermal storage season - thermal storage mode of buffer water tank

The system operates in the thermal storage mode of buffer water tank considering the demand of users for domestic hot water and the over-temperature protection of the water pit in the thermal storage season, as shown in Fig. 6(b). That is, the thermal collection system heats up the water at the bottom of the buffer water tank and fills it into the upper part of the buffer water tank. The thermal storage control modes can be divided into two types: temperature controlled thermal storage mode and continuous thermal storage mode according to the different control modes of thermal collection system.

Mode 3: Heating season - direct heating mode

In the heating season, the solar tower thermal collection system charges heat to the buffer water tank, and the buffer water tank supplies heat to the heating network, as shown in Fig. 6(c). The control mode of thermal collection system is continuous operation or temperature control mode, and the control mode of buffer water tank heating is constant temperature and constant flow heating mode.

Mode 4: Heating season - combined heating mode

In the heating season, the solar tower thermal collection system charges heat to the buffer water tank, and the buffer water tank supplies heat to the heating network. When the source (low solar radiation) charge (large heating load) mismatch leads to the buffer tank heating temperature is lower than the set value, and the temperature of the water pit is high, the combined heating of the water pit and the concentrating heat absorption system is adopted. The heating control mode of buffer tank is constant temperature and constant flow heat supply mode. As shown in Fig. 6(d).

The system operation is divided into two stages: thermal storage season and heating season during the system design. In order to meet the different energy needs of users, the system can provide domestic hot water or adjust the heating time according to the outdoor ambient temperature to ensure the thermal comfort of users.



Fig. 6: System operation mode

3.2. System control strategy

The control strategy is divided into the following situations during the seasonal solar thermal storage/heating

system operation, which according to the different operation stages and operation modes of heat storage season and heating season, combined with the operational performance of main components of the system. The logic diagram of the control strategy is shown in Fig. 7.

1) Operation control of solar energy collector subsystem

The solar collector subsystem in the system often operates in two modes: temperature-controlled operation mode and continuous operation mode according to different weather conditions or energy demand. Start or stop the thermal collecting circulating pump according to the set temperature, which taking the outlet temperature of the receiver as the monitoring object in the temperature-controlled operation mode. The thermal collection circulating pump will be closed at first when the temperature-controlled mode is selected for the thermal collection subsystem. The continuous operation control mode is mainly used to reduce the frequent start-up of the thermal collector circulation pump when the solar irradiation conditions are good. The two operation modes of the thermal collector subsystem can be selected according to the different heat demands in the thermal storage season and heating season in the actual operation of the system.

2) Thermal storage season, the operation control strategy of water pit or buffer water tank

The thermal collection subsystem selects the temperature control operation mode or continuous operation mode to preferentially charge heat to the water pit in thermal storage season. The thermal collection subsystem stops charging heat to the water pit and instead charges heat to the buffer water tank when the upper temperature of the water pit is higher than 90 $^{\circ}$ C considering the temperature resistance and service life of the water pit structure. The thermal collection subsystem pumps water from the bottom of the water pit, and then charges heat to the top of the water pit after heating by the thermal receiver during heat charging of the thermal collection subsystem to the water pit. It is essentially to control the start and stop of the thermal collection circulating pump by comparing the outlet temperature of the thermal receiver with the top temperature of the water pit when the system operating in the temperature control mode. And in order to prevent damage to the internal temperature stratification of the water pit, the outlet temperature of the thermal receiver is generally higher than the top temperature of the water pit.

3) Heating season, the operation control strategy of heating subsystem

The thermal collection subsystem preferentially charges heat to the buffer tank and controls the system by monitoring the temperature at the top of the buffer tank in the heating season. And the thermal collection subsystem charges heat to the water pit when the temperature at the top of the buffer tank is higher than 90 $^{\circ}$ C.

There are two modes for the system to supply heat to users through the buffer tank when the temperature at the top of the buffer tank is lower than the set heating temperature. One is the direct heating mode: Charging the buffer tank with heat if the thermal collection subsystem (temperature control mode or continuous mode) reaches the operating condition. And the other one is the combined heating mode: The water pit releases heat to the buffer tank when the thermal collection subsystem does not operate and the temperature of the water pit is higher than the top temperature of the buffer tank.



Fig. 7: The control logic of system

4. Summary of system operation

The first natural year of system operation is from April 11, 2018 to April 10, 2019. The operation period covers four operation modes and three control strategies in Section 3. And the relevant performance of the system is analyzed as follows according to the actual monitoring data of system operation.

4.1. Evaluation parameters of system

The solar energy calculation formula of heliostat field input solar tower thermal collection subsystem:

$$Q_{solar} = \int N_h \cdot A_h \cdot I_{DNI} d\tau \qquad (eq. 1)$$

Where N_h is the number of heliostats working normally at the current time. A_h is the daylighting area of a single heliostat, m²; I_{DNI} is normal direct irradiance, W/m².

The effective heat gain formula of the solar tower thermal collection subsystem:

$$Q_{col} = \int c_{p,w} \cdot m \cdot (T_{rec,out} - T_{rec,in}) d\tau \qquad (eq. 2)$$

Where Q_{col} is the effective heat gain of the receiver, J; $c_{p,w}$ is the thermal capacity of water J/(kg • °C); $T_{rec,out}$ is the outlet water temperature of the receiver, °C.

The calculation formula for thermal collection per unit lighting area of the solar tower thermal collection subsystem:

$$Q_a = \frac{Q_{col}}{N_h \cdot A_h}$$
 (eq. 3)

The calculation formula of the water pit heat loss:

 $Q_{loss} = Q_{CH} - Q_{DC} - \Delta Q \qquad (eq. 4)$

Where Q_{CH} is the heat charge of the water pit, and its calculation formula is:

$$Q_{CH} = c_{p,w} \int m_{CH} (T_{in,CH} - T_{out,CH}) d\tau \qquad (eq. 5)$$

 Q_{DC} is the heat supplied from the water pit in the heating season, and its calculation formula is:

$$Q_{DC} = c_{p,w} \int m_{DC} (T_{in,DC} - T_{out,DC}) d\tau \qquad (eq. 6)$$

 ΔQ is a variation of internal energy in water pit, and its calculation formula is:

 $\Delta Q = \rho_w c_{p,w} \int T_w - T_{w,0} \, dV \qquad (\text{eq. 7})$

The calculation formula of thermal storage efficiency of seasonal thermal storage water pit:

$$\eta = \frac{Q_{DC} + \Delta Q}{Q_{CH}} \qquad (eq. 8)$$

The calculation formula of solar fraction:

$$SF = \frac{Q_{sol}}{Q_{load}}$$
 (eq. 9)

Where Q_{sol} is the amount of heat supplied by solar energy for heating in the system, Q_{load} is the total heat load of the system.

4.2. Performance analysis of the solar tower thermal collection subsystem

Fig. 8 shows the statistics of annual monthly average environment temperature and cumulative normal direct radiation. In December, the monthly average outdoor environment temperature reached the lowest minus 7.5 °C, the highest monthly average environment temperature was 24.1 °C, and the annual cumulative normal direct radiation was 5580.2 MJ/m². Fig. 9 shows the annual operation data of the solar tower thermal collection subsystem. The highest monthly thermal collection was 50.9 MWh in October. It should be noted that only 20

days were counted in April 2018 and only 10 days were counted in April 2019 according to the actual operation of the system, so the monthly cumulative normal direct radiation and heat collection are low. It basically shows that the higher the cumulative normal direct radiation throughout the year, the more thermal collection of the solar tower thermal collection subsystem, and the greater thermal collection per unit daylighting heat collection area. The annual thermal collection is 325.0 MWh, and the annual thermal collection per unit daylighting area of the thermal collection field is 439.6 kWh/m².

The thermal collection subsystem has operated for 276 days since the system has been in operation for the first year and is still in the debugging and maintenance period. Therefore the efficiency of the collector is relatively low, and it can reach more than 50.8% under typical working conditions.



Fig. 8: System operation data Annual meteorological data

Fig. 9: Comparison of annual heat collection

4.3. The variation of soil temperature

Fig. 10 shows the cloud map of the soil temperature field every two months throughout the year. The x-axis in the figure represents the size from the wall of the water pit, and the y-axis direction is the depth direction of the underground soil. It is replaced by blank since no temperature measuring points are arranged in the soil under the water pit. The water pit goes through three stages: thermal charging, thermal storage and thermal release during the year of operation of the system, and the wall temperature of the water pit first gradually increases and then decreases. Due to the thermal conduction of soil and water pit wall, the heat conducts along the surface of the water pit wall in the radial and depth direction of the soil, and the soil temperature increases gradually. However, the soil itself is an infinite unsteady thermal transfer process, with many influencing factors and randomness, and its thermal analysis is extremely complex, which needs to be further explored.





Fig. 10: The cloud map of soil temperature field

4.4. System energy balance analysis

The thermal balance data of the system in this natural year is shown in fig. 11. The thermal collection system collects 450.8 MWh throughout the year, including 325.0 MWh from the solar tower thermal collection subsystem and 125.8 MWh from other thermal collection systems in the site. The internal energy of water pit increased by 94.5 MWh, and the average temperature of water increased from $13 \,^{\circ}$ C to $54.2 \,^{\circ}$ C (the maximum temperature). The average temperature of water at the end of the heating season was $42.7 \,^{\circ}$ C. The system provides domestic hot water and heating for the heating terminal with a total of 183.1MWh. Based on the calculation that 1 kg of standard coal can produce 0.0293 GJ heat(without considering boiler efficiency, pipe loss, etc.), the system can save at least 22.5T standard coal every year. And based on 2.662 t carbon dioxide produced by 1 t standard coal combustion, 59.9 t carbon dioxide can be reduced by the system. The thermal storage efficiency of the system can reach 62%. Based on the average annual heat load of buildings of 40 W/m², the annual building heat load of the system is 436.7 MWh, and the system provides total heat energy of 183.1 MWh to the heating terminal, so the solar energy guarantee rate is 49.4%.



Fig. 11: System heat balance diagram

As mentioned above, in the first natural year when the system was put into operation, it was still in the debugging and maintenance period, and the soil temperature was low, so the heat loss of water was large. And on the other hand, the heat in the water pit cannot be fully utilized, resulting in low utilization rate of water pit when the water temperature is below 40 $^{\circ}$ C because the heat pump and other facilities are not added in the system. Moreover, the water pit is in the thermal storage state above 40 $^{\circ}$ C for a long time, resulting in large heat loss. There is room for optimization of performance parameters in all aspects of the system with the continuous adaptation of the system.

5. Conclusion

Water pit for seasonal solar thermal energy storage is one of the important technical routes to realize "winter uses stored solar heat from summer" and "zero carbon heating." At present, water pit for seasonal solar thermal energy storage is the most mature, reliable and widely used technology of large-scale clean heating technology.

This paper mainly introduces the related technologies of the 3000 m^3 water pit long-term seasonal solar thermal energy storage system in Huangdicheng town, China. The operation in the first natural year is analyzed, and the feasibility of clean heating in north China is verified. The key research findings are as follows:

• The four operation modes of the system can not only deal with the unstable and discontinuous characteristics of solar irradiation, but also actively deal with the time-varying characteristic of users heat demand and heliostat field efficiency. The three control strategies can meet the different operation stages and modes of thermal storage season and heating season, and give full play to the design performance of the main components of the system.

• The annual thermal collection of the solar tower thermal collection subsystem is 325.0 MWh, and the annual thermal collection per unit daylighting area of the thermal collection field is 439.6 kwh/m². The efficiency of the heat collection field can reach more than 50.8% under typical working conditions. This project proved that the solar tower thermal collection subsystem could operate efficiently in the water pit for long-term seasonal solar thermal energy storage, and expanded the application idea for the existing concentrating solar thermal application technology.

• The system collected 450.8MWh of solar thermal energy in the whole year, the internal energy of water pit increased 94.5MWh, the average temperature of water pit increased from 13° C to 54.2° C, the average temperature of water pit at the end of heating season was 42.7° C, the thermal storage efficiency reached 62%, and the solar energy guarantee rate reached 49.4%.

• The thermal dissipation process of water pit is a very complicated unsteady process. Moreover, the thermal transfer and coupling process among water pit, insulation layer, soil and environment is a very challenging work. And the future research can be carried out from the water separator layout of water pit, economy of insulation layer, optimization of energy transfer and thermal exchange control theory etc.

6. Acknowledgments

The authors thank the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA21050200) for funding this project.

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Thermal inspection of water pit heat storages using drones

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Abstract

Water pit heat storages can be used to cover the mismatch between solar thermal generation and heat demand and achieve high solar thermal fractions in district heating systems. The most expensive part of such storages is the floating insulating lid, which is crucial to ensuring high efficiency by minimizing heat losses. So far, two different insulation materials have been used in the lids, namely Nomalén and LECA, both of which are sensitive to moisture. Therefore, it is important that leakages, which existing storages have been prone to develop, are fixed quickly. Manual inspection is costly and inefficient due to the lids' large surface area (>10.000 m2). This study investigates whether thermal drone imaging can identify leakages in pit storage lids by inspecting all existing pit storages in Denmark. The investigations identified leakages in two different pit storages and proved that drone thermal imaging is a very effective tool for leakage detection.

Keywords: drones, thermal imaging, pit thermal energy storage, heat storage, leak detection

1. Introduction

In Denmark, district heating supplies heat to more than 60% of residential consumers (Danish Energy Agency, 2017). The district heating networks utilize heat from various sources, including gas, waste incineration, coal, oil, combined heat power (CHP) plants, and surplus heat from industry. Renewables are also used, including solar thermal, geothermal energy, biomass, and heat pumps powered by renewable electricity (Lund et al., 2014). Although there is an effort to increase the share of renewables, there are many situations where the heat demand and supply do not coincide. This mismatch can happen either due to short-term weather-induced fluctuations or seasonal variations. For example, most solar irradiation in North and Central Europe is received between May and September, whereas two-thirds of the heat demand occurs between October and April.

As a solution to this problem, seasonal heat storages can store heat produced by solar thermal collector fields during summer and deliver it in winter (Mangold and Deschaintre, 2015). The mismatch between consumption and production typically limits district heating systems from achieving solar thermal fractions greater than 20%. However, using seasonal energy storages, solar thermal fractions can be increased up to 50% (Sveinbjörnsson et al., 2017).

One of the cheapest and most promising types of large-scale heat storage technologies is pit thermal energy storages (PTES), which have been demonstrated in combination with large solar collector fields in Denmark (Soerensen and From, 2011). In principle, a PTES is a large water reservoir that is used to store thermal energy. The storage duration depends on the application, ranging from days to months. First, a pit is excavated in the ground and is lined with a watertight polymer (Jensen, 2014). The excavated soil from the pit is used to form embankments around the pit, such that soil does not have to be transported off the site to minimize construction costs. Then, the storage is filled with treated water, which has the advantages of being inexpensive, non-toxic, allows stratification, and has a high thermal capacity (Schmidt et al., 2018). After the pit has been filled with water, it is covered with an insulated floating lid. One of the main advantages of the PTES technology is the low cost compared to other storage technologies and that high charge and discharge rates can be achieved.

The floating lid is the most expensive part of the storage; hence, many investigations have been performed for various designs and materials (Jensen, 2014). Nonetheless, liner ruptures or penetration has occurred in

numerous situations, causing water to leak into the lid, significantly reducing insulation performance. This leads to increased heat losses and reduces storage efficiency.

From experience, it has been proven that liner ruptures in the lids are difficult to locate due to their large surface area (>10.000 m2). In the past, leakages have been located by manual inspection, which is costly and inefficient. This paper presents experiences from drone thermal imaging of PTES, seeking to provide an effective and cost-efficient alternative to traditional methods.

2. Methods

In this section, the specifications of the PTES in Denmark are first presented, along with the corresponding insulation materials. Next, drone thermal imaging is introduced as a method for inspecting the lids of PTES for leakages due to the large lid areas. A major benefit of drone thermal leakage inspection is speed since the entire PTES lid area can be mapped in approximately 20 minutes. The specific setup used for the drone mapping is discussed in Section 2.3.

2.1. Lid insulation materials

Until 2020, only two different insulation materials have been used for PTES, namely Nomalén and LECA. Nomalén insulation is sold as mats made of cross-linked polyethylene foam (PEX) with a closed-cell structure, while LECA (Light Expanded Clay Aggregate) are small, expanded clay pebbles. However, there have been issues related to the usage of both technologies. Nomalén has in some cases collapsed to a fourth of its original thickness due to exposure to moisture and high temperatures (~90 °C) for long periods. LECA, on the other side, has a natural tendency to absorb water, and mechanical ventilation is necessary in order to dry out the material. Both of these issues decrease the insulating properties of the insulation material and increase the heat loss of the PTES. In Tab. 1, information about the existing PTES in Denmark is presented, along with the used insulation types.

Storage	Size (m ³)	Estimated lid area (m ²)	Insulation type	Reference
Dronninglund	60,000	8,300	Nomalén	(PlanEnergi, 2015, 2013)
Marstal	75,000	10,900	Nomalén	(PlanEnergi, 2013)
Toftlund	70,000	11,500	LECA	(Rambøll, 2016)
Gram	125,000	14,500	LECA	(PlanEnergi, 2016)
Vojens	200,000	22,500	LECA	(Rambøll, 2015)

Tab. 1: Infor	mation abou	t PTES in	ı Denmark
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2.2. Thermal imaging

Thermal cameras, also known as infrared or thermographic cameras, create images based on infrared (IR) radiation emitted by objects. They detect wavelengths in the infrared spectrum, typically from 750 to 1350 nm, whereas regular cameras detect visible light in the range of 400 to 700 nm. Therefore, thermal cameras do not directly detect temperature but instead rely on the principle that every object emits infrared radiation. Thermal cameras can detect radiation in the IR part of the spectrum that the human eye cannot see (OPGAL, 2018).

However, the conversion of infrared radiation to temperature can be complex. For example, in most cases, the emissivity of an object must be estimated since it affects the wavelength of the emitted infrared radiation. Emissivity is a surface radiative property, quantified as the ratio of emitted energy from a surface to that of an ideal blackbody surface. The emissivity range is from 0 to 1, corresponding to a perfect mirror and an ideal blackbody, respectively. A surface's emissivity depends primarily on the material and the surface finish, e.g., polished, painted, etc. Water affects emissivity, as wet or even moist surfaces have a different emissivity than dry. The water emissivity is 0.96, which results in damp areas of an object being erroneously detected as having a higher temperature. Surface water can also affect an object's temperature due to the evaporation of the water, reducing the temperature of the object. For obtaining an accurate surface temperature, images should be taken of dry surfaces, and the correct emissivity should be used, which can be adjusted in the settings of most thermal cameras.

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2.3. Drone thermal imaging

The drone used for the inspection of PTES is a DJI Matrice 200 equipped with a DJI Zenmuse XT2 640x512 resolution thermal camera. The Zenmuse XT2 is a dual camera that captures a regular image concurrently with the thermal image. The thermal camera has a 13 mm lens that detects radiation in the spectral band 7.5-13.5 μ m. Capturing both RGB and thermal images is helpful as it makes it easy to compare the features of the thermal image with that of a regular photo. For example, in the case of pit storage inspection, a thermal image abnormality might be caused by debris, which can be detected in the RGB image, and should not be further investigated.

The thermal investigation of the PTES was carried out during nighttime to avoid reflections from the sun. For this reason, RGB images of the storage were taken before the thermal inspection while it was still daylight. Pictures of the drone used can be seen in Fig. 1. The drone images were taken using the app DJI Pilot. Between 250-700 images were taken and stitched together for each inspection to form a large overall image called an orthomosaic. It was found that the images had to be taken at the height of 60 m for best orthomosaic results and a high level of detail. In order to ensure sharp images, the flight speed has to be set at a low value, depending on the battery capacity of the drone. For the orthomosaics presented in this study, a speed of approximately 2.3 m/s was used.

The stitching of the images was done using either DroneDeploy (commercially available) or OpenDroneMap (open-source). Unfortunately, neither software can generate a colormap for the orthomosaics for indicating the temperature at each spot. However, this is not of major concern, as the images are primarily used to detect differences in the relative temperature between different lid areas.



Fig. 1: DJI Matrice 200 equipped with a Zenmuse XT2 camera flying over the solar collector field in Vojens (left) and close-up photo (right) (Drones Made Easy, n.d.).

3. Results

This section presents the results of the investigations of the PTES using Nomalén, followed by the storages that use LECA as insulation. The presented thermal images are accompanied by a color bar indicating the temperature range on the storage's surface. The large differences between the temperatures of the plots are mainly due to the different ambient and sky temperature at the time of filming; thus, temperatures between plots should not be compared.

3.1. PTES using Nomalén

Nomalén is used as insulation material for the lid in the PTESs in Dronninglund and Marstal. Fig. 2 shows a thermal image and daylight photo of the Dronninglund PTES lid. One of the most noticeable observations in the thermal image is the many warm (yellow color) oval shapes on the lid. When comparing the locations and shapes of these to the RGB image on the left, it can be seen that they are water puddles. They are detected as warmer than the adjacent areas because the emissivity of water is higher than that of the lid surface. The water puddles can therefore not be compared with the surrounding areas; however, the puddles' temperatures can be compared with each other. By comparing the detected temperature of the different water puddles, it was identified that the puddle in the top left corner was warmer than the rest. The puddle temperature in the top left corner was 30.6 °C, while the average temperature of the rest of the puddles was 20 °C. The plant manager was informed about this finding, and the warmer pond was manually inspected. The inspection showed that

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the liner under the lid was torn in this area, and warm water from the storage was entering the lid. Afterward, the leak was fixed, resulting in a positive impact on the storage performance and lifetime of the insulation. By inspecting the thermal image in Fig. 2, a rectangular grid of thermal bridges can be noticed, corresponding to the gaps between the insulation mats underneath the top liner. The average temperature of the thermal bridges was 18 $^{\circ}$ C.



Fig. 2: RGB (left) and thermal (right) image of the PTES in Dronninglund.

In Fig. 3, the thermal and RGB images of the Marstal PTES are presented. As of April 2020, a new lid was installed consisting of twelve square sub-sections. Each sub-section is covered with gravel to ensure a slope towards the center, where a rainwater drainage system is located. Consequently, it is the only inspected PTES with no water ponds on its surface, and thus an easier assessment of the thermal image can be made. The bright yellow dots indicate the pump wells at the center of each sub-section. Additionally, several air vents and the three maintenance holes can be identified in the thermal image. The average temperature of the pump wells, vents, and maintenance holes was 20 °C. No issues were identified during the inspection that took place in October 2020. It can be observed that there was a small problem with the thermal image stitching at the top of the thermal image, though this did not significantly alter the thermal inspection.



Fig. 3: RGB (left) and thermal (right) image of the PTES in Marstal (October 2020).

A second inspection of the Marstal PTES was done in October 2021, a year after the first one, to verify the performance of the new lid technology. The results can be seen in Fig. 4. Overall, no significant differences were spotted between the two inspections, indicating that the performance of the lid has not degraded significantly during this period. However, a warmer area was detected at the connections of the left-most modules (marked with a white oval in Fig. 4). This is due to the separation of insulation covering the joint between the modules, which is thought to be caused by lid expansion. In general, the temperature of the hot spots where the insulation was separating was between 10 - 12 °C, whereas the temperature of the rest connections was around 8 °C. The separation of the insulation creates a thermal bridge and increases the heat

loss of the lid.



Fig. 4: RGB (left) and thermal (right) image of the PTES in Marstal (October 2021).

3.2. PTES using LECA

LECA is used as insulation material in the lid for the PTESs in Gram, Toftlund, and Vojens. Fig. 5 illustrates the orthomosaic for the PTES in Gram. This image looks vastly different from the PTESs in Dronninglund and Marstal. The reason for this is the different insulation materials used within the PTES lids. The brain-like pattern visible in Fig. 5 is thought to be due to heat convection within the lid. This phenomenon should be minimized as much as possible, as it enhances the thermal losses from the storage. The image clearly illustrates the presence of thermal bridges, which are most likely due to convection. The average temperature of the thermal bridges was 22 °C. It is suggested that smaller clay pebbles should be used in the future, or a convection membrane should be installed. Lastly, in Fig. 5, it was possible to identify a significantly warmer puddle (33 °C) on the lid near the top diffuser, indicating a potential leak.



Fig. 5: RGB (left) and thermal (right) image of the PTES in Gram.

In Fig. 6 and Fig. 7, the RGB and thermal images of the PTESs in Toftlund and Vojens are shown, respectively. Similar to Gram, these PTESs use LECA as lid insulation, and thus brain-like patterns due to convection can be observed in the thermal image. However, contrary to Gram, in both PTES, there seem to be areas of the lid where this phenomenon is more intense, indicating that either a thinner layer of LECA exists in these areas or that LECA is wet, resulting in higher heat losses.



Fig. 6: RGB (left) and thermal (right) image of the PTES in Toftlund.



Fig. 7: RGB (left) and thermal (right) image of the PTES in Vojens.

4. Conclusions

This article presents results from thermal inspection of pit thermal energy storages using drone thermal imaging. Two different technologies for lid insulation were investigated, namely Nomalén used in Dronninglund and Marstal, and LECA used in Gram, Toftlund, and Vojens. The results showed that although water ponds on the lid make thermal inspection more difficult, their relative temperature to each other can be used as an indication for leakages. In addition, the thermal images for Nomalén indicate more uniform heat losses than LECA, where brain-like patterns are created due to convection. Lastly, in some pit storages with LECA, areas with very intense brain-like patterns were identified, indicating possibly a thinner layer of LECA or moisture in the insulation. Overall, the performed investigations proved that drone thermal imaging is an effective tool for leakage detection in pit storages.

5. Acknowledgments

The research was financed by the Bjarne Saxhofs Fond.

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J-04. Storage Applications

Fluid Dynamic Analysis Inside a Solar Salts Prilling Power Using a Eulerian-Lagrangian Approach

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Abstract

Solar thermal storage technology has undergone significant development in recent years, especially about the types of storage fluids through the search for new mixtures that offer greater performance and energy storage autonomy. On the other hand, there is a new problem which is the way to remove these salts for a new use, at the University of Antofagasta there is a small-scale system for emptying these salts stored in a small tank. The system consists of a tower in which a mixture of salt is sprayed at high temperature and solidified by means of a heat transfer process inside the tower in which air circulates at room temperature. This document shows the hydrodynamic analysis of these particles inside the tower, the air and the interaction between them and the surrounding fluid. The analysis is performed using a Eulerian-Lagrangian approach using the Ansys Fluent R18.1 Computational Fluid Dynamics package through a CFD-DPM coupling.

Keywords: Solar salt, prilling, CFD, DPM, particle interaction.

1. Introduction

Prilling is a granulation process, in which a molten material is sprayed by means of a sprinkler into a cooling medium, generally air, and solidifies into particles under the influence of surface tension and gravity, droplets that fall freely form an almost spherical shape (Saleh and Barghi, 2016). During the fall through the ascending air, the droplets will cool until they begin to solidify into fine particles, which is calculated using a shrunken non-solidified core model (Ricardo et al., 2013). The most widely used droplet formation mechanism is generally by jet formation, which is subsequently broken into droplets. These disintegration mechanisms are found as a function of the flow rate of the liquid (Dumouchel, 2008). Understanding and reproducing the behavior of the gas-solid flow through mathematical models is of great importance to properly design some of the specific equipment for this process. The gas-solid flow has been used in various areas of the processing industry such as power generation, in the drying of granulated materials, in the transport of particles, in the combustion of coal in fluidized bed and in the industry of the oil refining. (Paz-Paredes et al., 2017)

In this work, the fluid-dynamic behavior inside a molten salt prilling tower for the termosolar industry is analyzed (Fig. 1). Molten salts represent an important element within solar thermal storage systems in concentrating solar thermal plants, these fluids store energy in the form of heat to be used in periods of operation of the plant in the absence of the Sun, the most used fluid is the so-called solar salt or nitrate salt, which is a eutectic mixture of 60% sodium nitrate (NaNO₃) and 40% potassium nitrate (KNO₃). Nitrate salt is considered the most important element in thermal energy storage (TES). Although nitrates may be capable of operating at high temperatures, it is understood that these will not reach the temperatures necessary to achieve power cycle efficiency goals. The salts used must have favorable thermo-physical properties for heat transfer and energy storage (Mehos et al., 2017).

The mixture is stable in air and has a low vapor pressure, it also has a variation in density during the phase change to solid state of 4.6%. These salts can be used in a temperature range of 260° C to about 621° C. As the temperature decreases, the salts begin to crystallize at 238° C and solidify at 221° C.



Fig. 1: Prilling tower diagram

Therefore, this work aims to study the fluid dynamic behavior of both the air (gas phase) that circulates inside this tower and the salt particles (discrete phase) that solidify as they descend through the tower. The study is carried out using a Eulerian approach for the gas phase and a Lagrangian approach for the discrete phase. These analyzes are carried out with the help of the Ansys Fluent 18.1 software using a coupled CFD-DPM model.

2. Process description

The analysis corresponds to the dynamic fluid behavior inside the tower shown in Fig. 1 where there is the entry of solar salt in liquid state at a temperature of 290°C and in which fine particles are obtained at the base of the tower of salt in solid state at a temperature of approximately 40°C. The tower operating conditions are shown in Tab. 2. While the properties of salt are shown in Tab.1

Property	Value	Unit	Reference
Specific heat	1,520	J kg ⁻¹ K ⁻¹	Mehos et al., 2017
Density	1,700	kg m ⁻³	Mehos et al., 2017
Melting/solidification point	220	°C	Mehos et al., 2017
Latent heat of solidification	161,000	J kg ⁻¹	Nissen, 1980g

The tower is located at the University of Antofagasta-Chile in the Antofagasta Energy Development Center, and its main function is solidification into fine molten salt particles located in a $1m^3$ capacity thermal storage tank.

Parameter	Valor	Unidad
Tower section	2x2	m
Effective tower height	6.5	m
Inlet air velocity	12.5	m s ⁻¹
Inlet salt flow	0.000056	m ³ s ⁻¹
Inlet salt velocity	9.161	m s ⁻¹
Inlet salt temperature	290	°C
Salt outlet temperature	40	°C
Air inflow temperature	20	°C

Tab. 2: Technical data and operating conditions of the tower

The prills produced have a relatively uniform size of about 0.5 mm and are produced by a sprinkler nozzle located on the top of the tower. The particle size distribution can be evaluated by sampling the particles that solidify on the granulation tower floor (Gezerman, 2020). Mono-dispersed granules can be obtained by operating the nozzle of the sprinkler in the Rayleigh jet breakdown regime, since a rapid transition to the crystalline state can cause disintegration of the particles (Saleh and Barghi, 2016). Attempts to delimit the regimes based on dimensionless numbers can be found in the literature, there are criteria for aircraft breakdown regimes found in the literature. In (Dumouchel, 2008) it is shown that these regimes are associated with typical values of the liquid Weber number We_L, the gaseous Weber number We_G and the Ohnesorge Oh number. The Weber number is a measure of the relationship between drag force and surface tension. The Ohnesorge number describes the relationship of viscous effects in the liquid and surface tension.

The Rayleigh jet rupture regime operates when the fluid velocity is large enough, but still low, this concept defines the relationship of the inertia of the liquid and the surface tension (Saleh, 2010). The liquid Weber number (salt), the gaseous Weber number (air) and the Ohnesorge number will be:

$$We_{l} = \frac{\rho_{l} \cdot d \cdot u_{l}^{2}}{\sigma} > 8$$
 (eq. 1)
$$We_{a} = \frac{\rho_{a} \cdot d \cdot (u_{l} - v_{a})^{2}}{\sigma} < 0.4$$
 (eq. 2)

Where, d is the diameter of the particle, σ is the surface tension of the liquid, ρ_l , ρ_a , are the density of the liquid and air respectively, u_l , v_a are the velocities of the liquid (particles) and air respectively. On the other hand:

(eq. 2)

$$0h = \frac{\mu_{l}}{\sqrt{\rho_{l} \cdot d \cdot \sigma}}$$
 (eq. 3)

In addition, secondary disintegration is performed when:

$$\frac{We_a}{Re} \ge 0.2 \tag{eq. 4}$$

3. Mathematical models

3.1. Mathematical model of the airflow inside the tower

For this study, the Ansys Fluent 18.1 Computational Fluid Dynamics (CFD) package is used, which is solved using a Eulerian approach. Computational fluid dynamics (CFD) modeling is used to investigate fluid flow patterns and fluid and particle trajectories under steady-state operating conditions. Airflow is modeled using the Eulerian approach, where turbulence is treated with Reynolds' averaged Navier-Stokes equations (RANS (Saleh, Barghi, 2016). Unlike other approaches to CFD methods that solve macroscopic property conservation equations, on the other hand, the Lattice-Boltzman (LBM) method describes the behavior of fluids on a mesoscopic scale (Dietzel and Sommerfeld, 2013). The Reynolds equations - Navier - Stokes Average (RANS) and the RNG k - ε model are presented below. (Saleh and Barghi, 2016)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \tag{eq. 5}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \left(\mu_{eff} (\nabla \vec{u} + (\nabla \vec{u})^{T}) \right) \qquad (eq. \ 6)$$

$$\frac{\partial \rho \kappa}{\partial t} + \nabla \cdot (\rho \kappa \vec{u}) = \nabla \cdot (\alpha_{\kappa} \, \mu_{\text{eff}} \nabla \kappa) + G_{\kappa} - \rho_{\epsilon} \qquad (\text{eq. 7})$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot (\rho \varepsilon \vec{u}) = \nabla \cdot (\alpha_{\varepsilon} \mu_{\text{eff}} \nabla_{\varepsilon}) + C_1 \frac{\varepsilon}{\kappa} G_{\kappa} - C_2 \rho \frac{\varepsilon^2}{\kappa} \quad (\text{eq. 8})$$

These equations represent the conservation equations of momentum and mass, which are used by the CFD solver (Wang et al., 2021). On the other hand, the turbulent viscosity will be:

$$\mu_{t} = \rho \cdot C_{\mu} \cdot \left(\frac{\kappa^{2}}{\varepsilon}\right) \tag{eq. 9}$$

Where, ε ; is the dissipation rate (m²/s³); κ ; is the turbulent kinetic energy (m²/s²) and Cµ is a constant. The effective viscosity shall be:

$$\mu_{\rm eff} = \mu + \mu_{\rm t} \tag{eq. 10}$$

Where: α_{κ} , α_{ϵ} are the turbulent Prandtl numbers; G_{κ} is the turbulent kinetic energy (kg/m s³) and C₁, C₂ are constant

3.2. Mathematical model of particles

In the analysis of salt particles, they are carried out from a Lagrangian trajectory approach using the Ansys Fluent 18.1 package using a CFD-DPM coupling. The different forces (viscous drag, lift force, buoyancy, etc.) that act on the Lagrangian particles along their trajectories are taken into account, as well as a stochastic behavior of the surrounding turbulent flow (Zahari et al., 2018). A particle in a granular flow can have two types of motion: translational and rotational. During its motion, the particle can interact with its neighboring particles or walls and interact with the surrounding fluid, through which momentum and energy are exchanged. Strictly speaking, this motion is affected not only by forces and torques originated by its immediate neighboring particles and the neighboring fluid, but also by distant particles and fluids through the propagation of disturbing waves. (Zhu et al., 2007)

In the Lagrange frame of reference, the trajectory is predicted by integrating the balance of forces in it while it is analyzed as a discrete phase. This balance of forces equates the inertia of the particle with the forces acting on the particle described in the following equation:

$$m_{p,i} \cdot \frac{d\overline{v_{p,i}}}{dt} = m_{p,i} \cdot \vec{g} + \sum \vec{F_c} + \vec{F_f}$$
 (eq. 11)

$$\sum \overrightarrow{F_{c}} = \left(\overrightarrow{F_{n}} \cdot \overrightarrow{n_{ij}} - F_{n} \cdot n_{ij}\right) + \left(\overrightarrow{F_{t}} \cdot \overrightarrow{t_{ij}} - F_{t} \cdot t_{ij}\right)$$
(eq. 12)

$$I_{p,i} \cdot \frac{d \, \vec{\omega}_{p,i}}{dt} = \sum \vec{T}_i$$
 (eq. 13)

Where $m_{p,i}$ \vec{g} represents the gravity of the particle, $\vec{F_f}$ is the total force of the fluid on each particle, $I_{p,i}$ is the rotational inertia of the particle, $\sum \vec{T_i}$ is the total torque acting on the particle, $\vec{v}_{p,i}$ is the linear velocity, $\vec{\omega}_{p,i}$ is the angular velocity of the particle, \vec{n}_{ij} is the normal direction from the center of the particle i al of the particle j; $\sum \vec{F_c}$ is the total contact force on each particle and is calculated using the Hertz-Mindlin model (no slip) (Wang et al., 2021). For a fine particle system, non-contact forces such as van der Waals and electrostatic forces must also be included. (Zhu et al., 2007)

3.3. CFD-DPM coupling

The numerical models of particle-fluid flows can be categorized into three methods, according to the treatment of the particles and the fluid phases: Eulerian-Eulerian methods, Lagrangian-Lagrangian methods and Eulerian-

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Lagrangian methods. In Eulerian-Eulerian methods, both the fluid phase and the particle phase are defined as continuous interpenetrated phases. A discrete phase model (DPM) is used in the Lagrangian frame of reference to track the movement of the particles, while a Eulerian formulation is used simultaneously for the continuous phase. The different forces (viscous drag, lift force, buoyancy, etc.) that act on the Lagrangian particles along their trajectories are taken into account, as well as a stochastic behavior of the surrounding turbulent (Zahari et al., 2018). For this work an Eulerian-Lagrangian approach is established, where the gas phase (air) is treated by means of a Eulerian approach and the discrete phase (particles) by a Lagrangian approach, the model is solved using the Ansys Fluent 18.1 software by means of a coupling. CFD-DPM. The drag force can be described by a constitutive equation defined as: (Cooper and Coronella, 2005)

$$F_{\rm D} = \frac{3 \cdot \mu \cdot C_{\rm D} \cdot Re_{\rm p}}{4 \cdot \rho_{\rm p} \cdot d^2}$$
 (eq. 14)

Where: μ is the viscosity of the particle (kg/m s); C_D is the drag coefficient of the particle; Re_p is the Reynolds number of the particle, and ρ_p is the density of the particle (kg/m³). On the other hand, although the air velocity in prilling towers ranges between approximately 1.37 and 2.45 m/s depending on the geometry of the tower and the air flow (Saleh and Barghi, 2016), for a stable airflow and the reduction of particle drag an air velocity of 1.0 m/s is recommended at a small Reynolds number (Re_{p)}. The range of Reynolds number and drag coefficient correlations (C_D)has been described for three regions: the Stokes law region (Re_p < 0.3), the intermediate region (0.3 < Re_p < 500), and Newton's law region (500 < Re_p < 2 × 10⁵). In the intermediate region, the drag coefficient is given as a function of the Reynolds number of the particle:

$$C_{\rm D} = \left(\frac{24}{{\rm Re}_{\rm p}}\right) \left(1 + 0.14 \cdot {\rm Re}_{\rm p}^{0.687}\right)$$
 (eq. 15)

Where:

$$\operatorname{Re}_{p} = \frac{\rho_{a} \cdot d \cdot (u_{p} - v_{a})}{\mu_{a}}$$
 (eq. 16)

Where: u_p is the velocity of the particle (m/s); v_a is the air velocity (m/s) and μ_a is the viscosity of the air (kg/m s).

4. Numerical modeling

4.1. Model validation

The study is carried out using the Ansys Fluent R18.1 package, using a CFD-DPM coupling model, where the gas phase is treated from a Eulerian approach, while the discrete phase from a Lagrangian approach. In Fig. 2 the configuration of the geometry is shown using the Ansys SpaceClaim Direct Modeler package, the dimensions of the tower are given in Tab. 2.



Fig. 2: Geometry Settings

The geometry is meshed using the Ansys Meshing PrePost environment, with an element size of 0.008m, a curvature-type size function, and inflation controlled by the program (Fig. 3). The grid has 108,258 nodes and 442,269 elements.



Fig. 3: Mesh configuration

In the processing stage, a double precision study is considered in a permanent regime considering the effect of gravity (9.81m/s), in addition, the two analysis models are defined for each phase. Turbulence is treated with the RNG k-epsilon model, while the discrete phase is simulated using a DPM model with an injection of particles at a rate of 0.0094kg/s and a velocity of 9.161m/s. The size of the particles is variable and ranges from 0.0000788mm to 0.5mm.



Fig. 4: CFD post processing

The Post-processed stage is analyzed using CFD-Post (Fig. 4) in which an XY sample plane is defined due to the symmetry of the tower, to analyze the air flow inside the tower.

5. Results and discussion

In this section we analyze the speed curves of the air ascent into the tower (velocity v of the Y axis) and the speed curve of the fall of the particles along the Y axis. Fig. 6 shows the diagram of air speed that goes from the base of the tower (12.5 m/s) to the top, in which a speed of approximately 1m/s is observed, which is within the ranges established in prilling towers. In addition, a significant decrease in the curve is observed when the air reaches half the height of the tower, due to the interaction with the salt particles.



Fig. 5: Variation of the rate of ascent of the air

On the other hand, the variation of the speed of fall of the particle is observed in Fig. 6, where there is an initial speed of 9,161 m / s which is the speed at which the jet leaves the sprinkler, it is also appreciated that the speed stabilizes (speed limit) approximately 3m from the height of the tower. Reaching a value of approximately 4m/s.



Fig. 6: Variation of the falling velocity of the particle

The limit or terminal velocity of the particle v_t can be determined as a function of the height of the tower according to the following equation: (Saleh and Barghi, 2016):

$$v_{t} = \sqrt{\frac{4}{3} \cdot \frac{d_{p} \cdot g \cdot (\rho_{p} - \rho_{a})}{C_{D} \cdot \rho_{a}}}$$
 (ec. 17)

This speed is the result of Newton's Law, which establishes that if a spherical particle is dropped into a fluid, it acquires an accelerated movement until it reaches a constant final speed, called the limit speed of fall or terminal speed. On the other hand, the analysis of the distribution of the number of particles inside the tower shows according to Fig. 7 shows that droplets of size between 9.14 μ m and 22.7 μ m prevail in a percentage range of between 5% and 27%.



On the other hand, the same range of particles occupy the largest area in the lower part of the tower, representing 30% of the area occupied by particles of this size (Fig. 8).



The volume of distribution of particles can be observed in Fig. 9 where those that occupy the largest volume are the largest particles, as well as what is shown in Fig. 10 which represents the accumulated volume that contrasts the values of particle sizes prevailing of $9.14\mu m$ and $22.7\mu m$. However, the maximum value of particle size which is $500\mu m$ or 0.5mm is the one considered to analyze the particle in a Lagrangian way.



6. Conclusions

The CFD-DPM simulation was carried out inside the molten salt prilling tower. Where the gas phase (air) was considered from the Eulerian point of view and the discrete phase (solar salt particles) from the Lagrangian point of view. The analysis of the variation in the speed of the circulating air inside the prilling tower shows that it has a significant decrease from the 3m height of the tower, reaching an almost constant value of 1 m / s. At that point it begins to stabilize due to the interaction of the air with the salt particles. On the other hand, the discrete analysis of the particles shows that it acquires a terminal velocity of 4 m / s from a height of 3m, which in the same way is due to the interaction with the fluid (air) in countercurrent.

During the modeling of particles inside the tower, it was observed that the particles that prevail in the particleparticle and particle-air interactions are the largest, in addition it is observed that these particles occupy a greater surface area within the gaseous medium as well as a higher volume. This is because the smallest particles are carried through the air into the environment in the form of aerosols. On the other hand, the size and configuration of the tower, as well as the configuration of the atomization process of the molten material, have an important significance in the distribution of particles inside the tower, as well as in the behavior of the air flow. Although the results of this study are specific to a tower of specific interest, the process can be extrapolated to similar or larger-scale cases.

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Numerical Model of System with Heat Pump and Latent Thermal Energy Storage

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Abstract

In the paper the numerical model of a system with heat pump and latent thermal energy storage has been developed. The system consists of water-water heat pump, latent thermal energy storage on the heat source side and two sensible thermal energy storages. The results obtained with numerical model of a presented system have been compared to experimental data, obtained using appropriate experimental setup. The comparison with experimental data is presented in terms of transient variations of temperatures for both water and paraffin, heat pump heating rate, heat pump cooling rate and compressor power as well as in terms of total delivered heat, consumed heat and consumed electrical energy by the heat pump.

Keywords: latent thermal energy storage, heat pump, system simulation

1. Introduction

The European Council has adopted strategies and targets for the next ten-year period, with the long-term goal of the EU becoming a net-zero greenhouse gas economy by 2050. According to the European Commission (European Commission, 2013.), 21% of the energy used for space heating comes from renewable sources, making the use of renewable energy sources for space heating a promising potential for achieving climate goals. One way to use renewable energy is heat pumps, because the energy produced by heat pumps is considered renewable if the annual performance factor of the heat pump is above 2.5 (European Parliament and of the Council on the Energy Performance of Buildings, 2013.). Most often, heat from outside air is used as the heat source for the heat pump evaporator, but the use of solar energy has the potential to further improve heat pump performance because heat pump efficiency is highly dependent on heat source and heat sink temperatures. Since both the availability of solar energy and the temperature of the outdoor air do not coincide in time with the highest heating demand on any given day, special care must be taken in the design of a heat storage tank to maximize heat pump efficiency, extend heat pump operating hours in the favorable mode, and reduce the number of ON / OFF cycles. Sensible thermal energy storages have traditionally been the most widely used due to their low investment cost. Recently, however, latent thermal energy storages are being increasingly used because they can store and release heat at a constant or nearconstant temperature, which can be beneficial in heat pump systems. In addition, defrost cycles can be avoided, which are common with air-source heat pumps at low outdoor temperatures and degrade heat pump efficiency. Finally, the required cooling capacity of the heat pump can be reduced, which would lower the investment cost of the heat pump (Pardiñas, 2017.). However, due to the low thermal conductivity of the phase change materials (PCM) used in LTES and the transient nature of heat transfer in LTES, the exact benefits of implementing LTES in heat pump systems remain to be investigated (Streicher, 2008.).

There are two main options for combining LTES and a heat pump - LTES connected to the heat pump condenser and LTES connected to the heat pump evaporator. The former can be used to match the time of economically efficient operation with the time of highest heating demand, and the latter to provide a higher evaporating temperature throughout the day.

Several authors (Streicher, 2008., Leonhardt, 2009., Agyenim, 2010.) have studied such systems where LTES is connected to the heat pump condenser. The main results were that a lower number of heat pump ON / OFF cycles and lower energy losses can be achieved when LTES is used, compared to systems with sensible thermal energy storage. Leonhardt et al. (Leonhardt, 2009.) reported that further research is needed to improve heat transfer in LTES, which could significantly reduce the volume of LTES. Another reason for connecting the LTES to the condenser is to store the excess heat from the heat pump when the heating energy demand is lower and the outdoor air temperature is higher, and use it later in the afternoon and evening when the outdoor air temperature is lower. This could help to eliminate peaks in the heating load and improve the average COP (Maaraoui, 2012.).

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Systems in which LTES is connected to the evaporator of the heat pump are also found in the literature (Comakli, 1993., Kaygusuz, 2000.). Usually, solar collectors are used in such systems. In this way, the heat pump can operate as an air source heat pump during the day, while the solar thermal energy can be stored in LTES to serve as a heat source for the evaporator later when the outdoor air temperature is lower and the heating demand is higher. Such systems could allow the heat pump to operate at a higher evaporating temperature and achieve higher efficiency (Comakli, 1993., Kaygusuz, 2000.).

Heat pump systems using latent thermal energy storage (LTES) have the potential to reduce the required installed power, shift working hours to a lower cost electricity tariff, reduce energy consumption and improve efficiency (Leonhardt, 2009., Agyenim, 2010., Kelly, 2014., Maaraoui, 2012., Comakli, 1993., Kaygusuz, 2000). With the aim of further investigating the advantages of these systems and establishing guidelines for sizing, a numerical model of a system with a heat pump and LTES was created in TRNSYS after which the numerical results were compared to experimental data.

2. System description

The schematic diagram of the experimental system is shown in Fig. 1. The system consists of a water-to-water heat pump, an LTES, two sensible thermal energy storages (STES), a heat load, solar collectors, a dry cooler, circulating pumps, an automatic control system, and measurement equipment with data acquisition system to track the temperatures and flow rates of the heat transfer fluid and the temperatures of the PCM within the LTES. During the LTES discharge process, the heat pump operates in heating mode and uses the heat from the LTES as a heat source for the evaporator. The heat needed to charge the LTES can be provided by a solar collector system or by the same heat pump operating during periods when ambient air heat can be used as a heat source. The use of the LTES as a heat source can lead to a shift in operating hours and help to overcome possible peak loads.



Fig. 1: Schematic diagram of the system with heat pump and LTES

For measuring temperatures of heat transfer fluid eight PT100 temperature sensors were used. Temperatures were measured at the outlet and inlet of the heat pump condenser and evaporator (T1-T4), in the sensible thermal energy storage tanks (T5, T6), and at the outlet and inlet of the LTES (T7, T8). The temperature of the paraffin inside the LTES was measured with thermocouples at different locations inside the LTES (T9). Three ultrasonic flow meters have been installed to measure the volumetric flow rates of the heat transfer fluid through the heat pump condenser and evaporator and through the LTES.

An application has been created in Labview software and used to read and store the measured values of temperatures and volume flows, as shown in Fig. 2.



Fig. 2: Data acquisition during the experiments

The Labview application has been run on a personal computer during the experiments and allowed real-time monitoring of the measured values. The heat pump and sensible heat storage tank connected to the heat pump condenser are also shown in Fig. 2.

The LTES and the flow and temperature control system are shown in Fig. 3.



Fig. 3: LTES and flow and temperature control system

The PCM inside the LTES was Rubitherm's RT25 paraffin (Rubitherm GmbH, 2018.). The heat transfer fluid flows through the tubes while the paraffin fills the shell side of the LTES. The thermal and physical properties of paraffin RT 25 are given in Table 1.

Melting/solidification temperature range	22-26 °C
Latent heat	170 000 J/kg
Thermal conductivity	0.2 W/mK
Specific heat capacity	2000 J/kgK
Density solid/liquid	880/760 kg/m ³
Kinematic viscosity (liquid)	4.7 mm ² /s

Tab. 1: Thermal and physical properties of RT 25 (Rubitherm GmbH, 2018)

A constant temperature of the heat transfer fluid at the inlet of the LTES was ensured by a three-way control valve that was continuously adjusted by the control system.

Experiments were completed when all thermocouples indicated temperatures above the melting point in the charging analyses and temperatures below the melting point in the discharging analyses.

Another measurement has been performed on the heat pump to obtain data on the normalized capacity and power consumption of the heat pump as a function of the entering source fluid temperature and the entering load fluid temperature. Using the measured volumetric flow rates and the temperature difference of the heat transfer fluid at the condenser and evaporator inlets and outlets of the heat pump, the heating and cooling capacities were calculated, while the compressor capacity was measured with electricity power analyzer. These data were used to model the performance of the installed heat pump.

3. System modelling

The transient numerical model of the system was developed in Trnsys (TRaNsient SYstems Simulation Program). It consists of more than 20 components called types, which are mathematical models of the actual components such as heat pump, energy storage, circulating pump, etc. (see Fig. 4).



Fig. 4: System model in TRNSYS

For modelling of sensible thermal energy storages Type 534 was used (TESSLibs, 2017.). The sensible thermal energy storage is uniformly divided into isothermal nodes, each of which thermally interacts with neighboring nodes through the following mechanisms: Thermal conduction between nodes and by fluid motion caused by natural destratification - mixing due to temperature inversions in the tank. For modelling of the latent thermal energy storage

Type 840 was used (Schranzhofer, 2006.), which is based on the enthalpy approach, where enthalpy is a continuous and invertible function of temperature. A water-to-water heat pump was modelled using type 927 (TESSLibs, 2017.). This type models a single-stage heat pump that requires the user to provide data for the normalized capacity and power consumption of the heat pump as functions of entering source fluid temperature and entering load fluid temperature, based on which the evaporator and condenser outlet temperatures are calculated. Other types used to model the system were Type 654, which models a single speed circulating pump; Type 709, which models a circular pipe filled with liquid; Type 647, Type 649, and Type 953, which model liquid mixing valves; Type 911, which models a differential controller with lockouts; and a general forcing function model - Type 14. The time step size was one minute.

4. Results and discussion

The solidification and melting processes of the PCM have been analyzed both experimentally and numerically, and the comparison is presented for the solidification process. The numerically and experimentally determined temperatures at positions T1, T3, T7 and T9 are shown in Fig. 5. The operating conditions were as follows: heat transfer fluid temperature at LTES inlet was T8 = 7 °C and mass flow in LTES loop was $m_{LTES} = 830$ kg/h, heat transfer fluid mass flow in heat pump condenser loop was $m_{COND} = 4700$ kg/h and in heat pump evaporator loop was $m_{EVAP} = 9620$ kg/h. The initial temperature of the PCM was 30°C.



Fig. 5: Comparison of numerically and experimentally obtained temperatures at heat pump condenser outlet (T_1) , evaporator outlet (T_3) , LTES outlet (T_7) and average PCM temperature (T_9) for heat transfer fluid temperature at LTES inlet $T_8 = 7$ °C and mass flow $m_{LTES} = 830$ kg/h, heat transfer fluid mass flow in heat pump condenser loop $m_{COND} = 4700$ kg/h in heat pump evaporator loop $m_{EVAP} = 9620$ kg/h

The transient variations in the temperatures of the heat transfer fluid at the outlet of the condenser, evaporator, and LTES, as well as the temperatures at PCM, are shown in Fig. 5. Sudden jumps in condenser and evaporator outlet temperatures indicate the beginning of the heat pump cycle ON and sudden drops indicate the end of the heat pump cycle. Good agreement in ON-OFF cycle dynamics between the installed heat pump and the model can be seen in the form of nearly simultaneous jumps and drops in condenser and evaporator outlet temperatures throughout the time period shown. The differences in condenser outlet temperatures are due to the limitations of the Type 927, which does not account for the transient nature of the heating rate at the beginning of the ON cycle. Nevertheless, good agreement can be seen in the transient temperature variations between the temperatures obtained with the numerical model and the measured temperatures.

The comparison of numerically obtained heating rate (Q), cooling rate (Q_0) and compressor power (P) with experimental data during the first ON-OFF cycle of the heat pump is shown on Fig.6.



Fig. 6: Comparison of numerically obtained heat pump heating rate (Q), cooling rate (Q_0) and compressor power (P) with the experimental data

The first ON-OFF cycle is considered to be the first ON cycle in a day when the sensible thermal energy storages (STES1 and STES2) connected to the heat pump condenser and evaporator are at the same temperature. The heat pump is turned ON and remains in operation until the temperature of the heat transfer fluid at the outlet of the condenser reaches 50 °C. At this time, the heat pump is switched to OFF. Since the heat transfer fluid at the outlet of the condenser reached 50 °C after about 15 min, the total operating time of the presented cycle was approximately 15 minutes. Due to the aforementioned limitations of the TRNSYS Type 927 heat pump model, which does not account for the transient nature of the heating rate, cooling rate, and compressor capacity at the beginning of the ON cycle, some discrepancy is observed between the installed heat pump performance and the model performance. In order to quantify this discrepancy and justify the application of the model, the heat supplied by the heat pump (Q), the heat consumed (Q0) and the electricity consumption (P) calculated with the numerical model and the experimental data were compared and presented in Table 2.

 Table 2: Comparison of heat pump delivered heat (Q), heat pump consumed heat (Q_0) and compressor electricity consumption (P) obtained numerically with experimental data

	Model	Experiment	Discrepancy
<i>Q</i> [MJ]	81.07	73.48	10.3 %
$Q_0 [\mathrm{MJ}]$	48.86	44.91	8.8 %
<i>P</i> [MJ]	28.67	25.00	14.6 %

The highest observed discrepancy was 14.6% for electricity consumption, while heat supplied and consumed were 10.3 and 8.8%, respectively.

5. Conclusion

The heat energy stored in the LTES can potentially be used as a heat source for the heat pump during the late afternoon and evening hours, allowing for a higher heat source temperature and more efficient operation of the heat pump compared to operation with outside air as the heat source. A numerical model of the system with heat pump and latent thermal energy storage was created and compared to experimental measurements. The comparison of numerically obtained and measured temperatures has been presented for the whole system during a solidification process. Additionally, the calculated and measured heat pump delivered heat, consumed heat and electricity consumption have been compared and presented. The presented numerical model can be used for further analysis of similar systems to further investigate the advantages of combining LTES with a heat pump.

6. Acknowledgement

This work has been supported in part by Croatian Science Foundation under the project HEXENER (IP-2016-06-4095) and in part by the University of Rijeka under the project number "uniri-tehnic-18-69".
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L-01. Renewable Resources Assessment

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Abstract

Ground-level solar spectral measurements, which are scarce in general, are important to assess the performance of photovoltaic (PV) technologies. Indeed, PV materials have different responses with regards to the spectral distribution of solar radiation. In order to study the impact of solar spectral variations on PV, the terrestrial solar spectrum needs to be characterized and quantified. In this work, we present the analysis of solar spectral irradiance measurements recorded for a period of one year, in desertic atmospheric conditions. The spectral measurements are done on a tilted surface at an angle equal to the latitude of the studied location, and wavelength range from 350 nm to 1050 nm. The analysis covers several temporal resolutions. Moreover, the local spectral variations are characterized in terms of the variations in the average photon energy (APE) parameter as well as the useful fraction (UF) parameter specific to different PV technologies.

Keywords: Solar spectral measurements, PV performance, APE, UF, Desert conditions.

1. Introduction

The performance of PV devices is usually studied under Standard Test Conditions (STC) of specific meteorological and solar radiation parameters; these correspond to a cell temperature of 25° C, an irradiance of 1000 W/m² with a standard reference spectrum of a clear day at air mass 1.5 (AM1.5) (ASTM, 2003). Under real environmental conditions, the PV performance changes depending on the local variations of the specific parameter. In general, the broadband solar irradiance has the largest influence on PV module performance. However, the solar radiation spectrum can also have noticeable impacts. When compared to the reference spectrum, the actual solar spectrum at ground level varies continuously, with the changing atmospheric contents and the relative optical path of the radiation through the atmosphere. These variations in the spectral distribution of the incident solar radiation can influence the PV output under real outdoor conditions, given that different PV devices exhibit different spectral responses, with an effective spectral range specific for each (Betts, 2004). The spectral gains or losses under real operating conditions as compared to the reference conditions are quantified using a spectral factor parameter that takes into account the spectral response of the different PV technologies, and the variations of the incident solar radiation spectrum.

Several authors have studied the impact of the spectral variations on PV systems, using different module technologies at different geographical locations. Wilson and Hennies (1989) assessed the spectral variations effect on the short circuit current of GaAs and monocrystalline, polycrystalline and amorphous Si solar cells. Fabero and Chenlo (1991) studied the influence of the annual and daily variations of the spectral solar irradiance on mc-Si and a-Si devices in Spain. Nann and Emery (1992) studied the spectral effect on seven solar cells and found that the efficiencies of amorphous silicon cells differ by 10% between winter and summer months. Williams et al. in 2003 reported that the spectral impact is less pronouced for PV technologies with narrow band gaps, i.e., wide spectral response, such as CIGS or c-Si, but have a noticeable effect on materials with wide band gap, such as a-Si or CdTe. A study in Hungary (Kocsány et al., 2010) found that, in clear days, polycrystalline silicon performs better than amorphous silicon when the red and infrared bands dominate the spectrum. Virtuani and Fanni (2014) found that c-Si performs better than a-Si for a red-shifted spectrum, while a-Si outperforms c-Si for a blue shift. Alonso et al. (2014) studied the spectral effects on eight solar cell technologies and found that narrower band gaps result in higher sensitivity to spectral changes. According to Dirnberger et al. (2015), the spectral variations resulted in output changes ranging from 0.6% for small-band-gap CIGS, to 3.4% for a-Si, with c-Si (2 types) and CdTe in between, with 1.1 to 1.4%, and 2.4%, respectively. More recently, Yandt et al. (2017) studied the spectral effect on multijunction devices and reported that mismatches between junctions result in additional losses and require more detailed spectrum studies. It is thus important to study and characterize the solar spectral distribution in a specific location, for at least a period of one year, and consider the resulting variations when evaluating the outdoor performance of PV modules.

This work presents a study of the variations of the solar spectrum in a highly aerosol-loaded atmosphere, including the analysis of the local changes of the spectral distribution of the solar radiation in the range 350 nm to 1050 nm,

covering different seasons and weather conditions in a one-year period. It also includes the analysis of two parameters useful to characterize the spectral effect: the Average Photon Energy, or APE (Minemoto, 2009), commonly used to show the shift towards the red or the blue part of the spectrum, and the Useful Fraction, or UF (Gottschalg, 2003), used to account for the specific spectral response of PV devices under real local solar spectrum conditions.

2. Methodology

The solar spectral radiation was acquired using an EKO MS-700 spectroradiometer. The sensor consists of a highquality hermetically sealed dome and diffuser that measures the spectral irradiance in the range 350 to 1050 nm, with a spectral resolution of 10 nm, wavelength accuracy of \pm 0.3 nm, and a cosine error < 7%. The spectral radiometer was installed on a tilted surface at the optimal tilt of PV panels for the location under study, namely Doha, Qatar (25° N, 51° E). The solar spectral irradiance data was collected every 5 minutes from sunrise to sunset, recording 701 spectral measurements at each data acquisition, for a period of one year.

The Average Photon Energy, defined as the average energy per photon of the spectrum, is calculated according to:

$$APE = \frac{\int_0^{\lambda} G(\lambda) d\lambda}{q \int_0^{\lambda} \Phi(\lambda) d\lambda}$$
 (eq. 1)

Where $G(\lambda)$ is the spectral irradiance, Φ is the photon spectral flux density and q is the electron charge. The integration is done over the spectral range of the spectroradiometer.

The Useful Fraction, the part of the solar spectrum which is usefully converted into electricity by the specific PV device, is calculated as follows:

$$UF = \frac{\int_0^{\lambda} G(\lambda) d\lambda}{\int_0^{\infty} G(\lambda) d\lambda}$$
 (eq. 2)

Where $G(\lambda)$, the spectral irradiance, is integrated over the spectral response of the considered PV technology at the numerator, and integrated over the whole solar spectrum at the denominator.

3. Results and discussion

As an example, the spectral irradiance collected in Doha in April 2015 is shown in Figure 1 for various times during a clear day (top graphs), and a dusty (more heavily in the morning) day (bottom graphs). On the right side, the daily profiles of the broadband solar radiation of those particular days are shown to confirm the conditions of the day.





Fig. 1: Measured spectral solar radiation for various times in a clear day (top), and a dusty day (bottom) of the same month, in comparison with the ASTM AM 1.5 reference spectrum.

The absorptions of different atmospheric components at specific wavelengths are clearly seen in the spectral distribution plots. The variations within one day are due to the different paths that the solar radiation has to cross to reach the earth surface, as well as to the different atmospheric conditions encountered along this path. The path length is quantified by the Air Mass (AM) parameter, which is the ratio between the length of the path that the sun takes through the atmosphere to the shortest possible path length when the sun is directly overhead. Figure 2 shows the variations of the air mass in Doha, during one day, and during a full year period at solar noon, the solar noon being the time of the day where the sun reaches its highest apparent position in the sky, i.e. the smallest AM in each daily plot. During one day, AM decreases and increases exponentially in the morning and afternoon respectively, with the lowest value observed at solar noon. The annual variation of the AM at solar noon in Doha shows that the AM values range between 1 and 1.5 with the lowest value ~ 1 observed in June (day 172 in Figure 2, right side). The different path lengths and their different contents affect the absorption and scattering of the solar radiation and hence lead to a different solar spectral distribution in one day, and throughout the year. The influence of the atmospheric particles on the variations of the spectral radiation is obvious when we compare the spectrum plot of the clear day and dusty day in Figure 1 at a specific time (same-color line in the top and bottom plots), knowing that the change in AM is small between these two days (0.2 %). For the clear day, the irradiances are higher and the variations per wavelength are higher when compared to the dusty day during the morning hours. This is due to the strong absorption of the solar radiation by the dust particles, leading to lower variations per wavelength as the sun passes through the atmosphere, mainly in the visible wavelength range between 400 nm to 700 nm.



The reference spectrum shown in red in Figure 1 is the American Society for Testing and Materials (ASTM) G-173 spectrum, representing the global total solar spectral irradiance on an inclined plane of 37° tilt toward the equator and for specified atmospheric conditions, namely the 1976 U.S. Standard Atmosphere and an absolute air mass of 1.5, etc. This spectrum is used as a common reference for evaluating PV materials. The reference spectrum plotted here is adapted from the ASTM G-173-03 table published as a spreadsheet on the NREL website (NREL). It is noted that the spectra approaching the reference one in Figure 1.a and b are those measured at 11:30 hrs, the closer time of the day to the local solar noon. However, for the remaining time of the day, with the conditions being different, the measured spectral distribution deviates from the reference conditions, depending on the position of the sun and the atmospheric contents as discussed above. In order to understand better the daily variations of the spectral distribution, we calculate the average irradiance per wavelength at the same time stamp for all the days of one month, and we

determine the standard deviation relative to the average during this month. Figure 3 shows a sample of this calculation for two months, April and August, at two different time stamps, 9:00 and 11:45 am. The colored bands indicate the standard deviation bars of the averaged values, i.e. the variations of the spectral distribution during one month. For comparison, we also plot the reference spectrum AM1.5, the spectrum in blue. In April, similar spectral variations are seen in the morning (9 am) and around solar noon (11:45 am). In August, the variations are more pronounced than in April, and at solar noon they are larger than in the morning. These large variations indicate that in August the atmospheric contents are highly variable, leading to the large changes in the spectral distribution from a day to another. The closer look in Figure 4 shows bigger variations within the visible range.



Fig. 3: Averaged spectral distribution in a month with one standard deviation bands. April (left) and August (right).



Fig. 4: Averaged spectral distribution in August with one standard deviation bands for different wavelength ranges. Ultraviolet (left), visible (middle) and near infrared (right).

As seen above, the spectral distribution of the solar radiation exhibits intra-day, daily, and seasonal variations throughout the year. Since PV cells nominal power is determined against the reference spectrum AM1.5, it is important to evaluate the spectral response of PV cells in real outdoor conditions at the location of interest, and to determine the deviations of the real measured spectra against the reference one. However, it is a cumbersome process that involves a huge amount of data when doing this analysis for each measured spectrum; for the study here, the spectrum is measured every 5 minutes, each time with 701 data points covering the range of 350 to 1050 nm. Determining one quantity, the average photon energy (APE), was found to be a suitable method that provides information about the shift of the spectrum to the blue or red wavelengths, and allows an easier way to classify the PV technologies under the real spectral conditions (Norton, 2015). The reference value APEref ~ 1.88 eV is calculated for the reference spectrum using equation 1 and considering the spectral range of the spectroradiometer (350-1050 nm). A spectrum with an APE lower than APEref is shifted towards the red wavelengths, and higher values indicate a shift towards blue wavelengths.

In the following, we study the variations of APE in Doha, for several temporal resolutions. Figure 5 shows the frequency distribution of the 5-min APE (left) and daily APE values (right) calculated for one year, in Doha. The mean value of both distributions is equal to APEref. Considering the full year, the 5-minute values are shifted toward the blue wavelengths, and the daily values are equally distributed around the average with higher frequency for the values above the average, so that the overall spectral distribution in Doha is shifted towards the blue wavelengths.



Fig. 5: Frequency distribution of APE in one year in Doha. 5-min APE (left) and daily APE (right).

Figure 6 shows the variations of the hourly APE for the two days studied in Figure 1. Comparing the clear and the dusty day, we can clearly see the low APE values in the morning hours due to the dust layer in the atmosphere, shifting the spectrum of the solar radiation to the red wavelengths (APE less than the reference APE). With the dust layer decreasing in the afternoon for the dusty day (see the daily solar radiation profile in Figure 1), APE increases to stabilise around the average, decreasing slightly around the sunset hour. To note that for this particular day in April, the sunset hour is at 17.50 pm, however the 5-min APE values used here are only provided until 17.30 pm, so the corresponding hourly APE at sunset hours (17 to 18), timestamp 17, uses only 6 APE entries, providing thus a higher APE value than expected. For the clear day. The hourly APE variations look more stable during the clear day.



Fig. 6: Hourly APE during a clear and a dusty day.

Figure 7 shows a heatmap of the hourly APE values for one year in Doha, where the x-axis presents the hour of the day and the y-axis the hourly APE values. The color-coded scale on the right indicates the frequency distribution (in %) of APE at the corresponding hour and APE bin through the year, from purple (lowest) to red (highest); for instance, the green color in the middle means that 0.8 % of the APE values fall within the corresponding hour and APE bin. The red horizontal line is the reference APE. In general, APE values higher than the average are more frequent, with the highest frequencies seen around solar noon. More variations of APE are observed in the morning and afternoon hours due to large AM and exponential decrease/increase of AM at these hours; the asymmetry, however, reflects the more foggy early morning conditions seen in Doha. The overall spectral distribution indicates the shift to the blue wavelengths (APE higher than APEref) for all the hours of the day.



Fig. 7: 2-D histogram of hourly APE for one year in Doha. The red horizontal line indicates the reference value.

Figure 8 shows the monthly variation of APE, as compared to the reference APE value of 1.88 eV of the standard AM1.5 spectrum in the range of 350–1050 nm. High values of the monthly-averaged APE are noted in general, with values shifted towards the blue part of the spectrum for almost 8 months from March until October (October being on the edge). For the winter months, the APE is lower and indicates a shift towards the red wavelengths.



Fig. 8: Monthly variation of APE, as compared to the reference value in red.

In order to study the effect of spectral shift on a specific PV technology, the useful fraction (UF) parameter that considers the active spectral wavelength band of PV materials is used. In this contribution, we consider two cases with useful spectral range from 350-800 nm and 350-900 nm. The two wavelengths 800 nm and 900 nm correspond to the upper wavelength limit of the spectral response of a-Si and CdTe, respectively. Due to the range of the sensor used here, we use 350 nm as the lower limit of the useful spectral range. The UF reference is calculated from the reference spectrum AM1.5 in the measured spectral band (350-1050 nm); UF is 0.76 for the spectral range 350-800 nm and 0.88 for the 350-900 nm spectral range. Figure 9 shows the frequency distribution of UF for one year in Doha for the two spectral ranges considered here. The red line is the UF reference value. Figure 10 (left side) shows the monthly-averaged UF, with bars at each monthly value indicating the standard deviation of UF during the corresponding month. The dashed horizontal lines are the reference values.



Fig. 9: Frequency distribution of useful fraction (UF), up to 800 nm (left) and up to 900 nm (right). The red vertical line is the reference UF.



Fig. 10: Monthly variations of useful fraction (UF) for two PV technologies. Averaged values with one-standard deviation bars (left), standard deviation in percentage (right).

The frequency distribution of UF values in Figure 9 shows that more UF values are above the reference spectrum value for the two ranges studied here. Higher UF values are calculated for the higher spectral range as expected. In figure 10 (left), the monthly variations shows that the high UF values occurs mostly at summer months, from April to October, with low variations in UF (smaller standard deviation bars), while the winter months show lower UF values but with larger variations. UF variations during each one-month period are higher for the smallest spectral band for all the months as seen on the right side of Figure 10, showing the relative standard deviations of UF.

4. Conclusion

Solar PV technologies are rated under the specific conditions of the reference spectrum AM1.5. However, due to intra-day and annual variations of the path lengths of the solar radiation, as well as the changes in the atmospheric contents, the real spectrum exhibits significant variations. It is thus crucial to characterize the spectral distribution in locations of interest for PV technologies, in order to determine the effect of these variations on the performance of PV cells in real outdoor conditions.

In this work, we presented the analysis of solar spectral irradiance measurements recorded for a period of one year, in desertic atmospheric conditions. The spectral measurements are done on a tilted surface at the latitude of the studied location, and for a spectral range from 350 nm to 1050 nm. The analysis covered several temporal resolutions, and the local spectral variations were characterized in terms of the variations of the two parameters, the average photon energy (APE) and the useful fraction (UF, which depends on the spectral range of the different PV technologies). From this analysis, we found that the overall spectral solar radiation in Doha is shifted towards the blue wavelengths for the 'summer' months and towards the red wavelengths during the 'winter' months. However and independently from the season, these averaged conditions change when local conditions such as dusty conditions occur, and shift the spectrum towards the red wavelengths. When studying the spectrum in the wavelength ranges that are similar to the response of some technologies, it was found that PV technologies with smaller wavelength range are more affected by the local spectral variations. This emphasises the importance of including the characterization of the solar spectral irradiance measurements in the evaluation of PV modules performance and yield in real operating conditions.

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Why Natural Cleaning of Solar Collectors Cannot be Described Using Simple Rain Sum Thresholds

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Abstract

This study investigates parameters describing the modelling of natural cleaning by precipitation in soiling models for solar collectors. Approaches assuming that the solar collector is cleaned completely if a daily rain sum threshold is exceeded are investigated with the help of more than three years of soiling and natural cleaning data at CIEMAT's Plataforma Solar de Almería in Spain. It is found that the natural cleaning completeness by rain cannot be described well by using only a threshold of the daily rain sum. We discuss the dependence on further parameters, e.g. the existing soiling levels, the rain direction dependent on wind speed, the collector orientation, the kind of soiling, the collector surface properties and several more. Considering the rain/wind and collector orientation is especially important for the modelling of natural cleaning of tracked collectors as the effective rain sum hitting the collector and the runoff speed is expected to change drastically with the orientation of the collector.

Keywords: Soiling, Natural Cleaning, Photovoltaic, Solar Energy

1. Introduction

The accumulation of aerosol particles on photovoltaic (PV), concentrated solar power (CSP) or non-concentrating solar thermal collectors causes soiling losses and can vary dependent on the implementation site and also with time. Those losses have been studied at several sites around the world and different analytical soiling models have been implemented to describe soiling losses dependent on local aerosol deposition and rainfall pattern (Picotti et al., 2017, Wolfertstetter et al., 2019). If information of the local expected soiling rate and precipitation would be available for the site of interest, the soiling model results could be considered within PV or CSP performance models and a tradeoff between minimizing the soiling losses and the induced cleaning costs of the collectors could be predicted.

One key effect is the natural cleaning of the solar collectors by rain. It can be observed that light rain rather soils the collectors while heavy rain reduces the soiling levels or cleans the collectors completely. For simplification, in most PV soiling models which can be found in literature (e.g. Hamond et al., 1979; Kimber et al. 2006; Caron and Littman, 2013; Mejia et al., 2014; Coello and Boyle, 2019), a fixed threshold for the daily rain sum is defined assuming a completely cleaned collector if the threshold is exceeded. Due to the lack of detailed information on the site and time dependent particle removal mechanisms, this simplification can be used for a rough estimation of natural cleaning of collectors, but several natural cleaning events might be missed by this simplification.

In this work, soiling ratios measured with pairs of reference cells mounted at CIEMAT's Plataforma Solar de Almería (PSA) during more than 3 years (2018-2021) are analyzed. The soiling rates and natural cleaning events are compared with measured precipitation and thresholds found in literature are evaluated. Different important mechanisms influencing the natural cleaning process are discussed and further geometrical considerations are presented to enable an enhanced modelling of natural cleaning events of solar collectors.

2. State of the Art: Threshold Approaches to model Natural Cleaning

In literature, several approaches to estimate the effect of natural cleaning by rain events have been found. Micheli and Muller (2017) and Micheli et al. (2018) investigated for example the correlation between the *SRatio* and rainy days while a rainy day has been defined with daily rain sums of more than 0.3 to 1 mm. In studies of Kimber et al. (2006), Hamond et al. (1979), Caron and Littman (2013), Mejia et al., (2014) and Coello and Boyle (2019), Micheli and Muller (2017) or Micheli et al. (2018) thresholds for the daily rain sum between 0.3 and 10 mm for a complete recovery of the efficiency of a solar collector have been assumed (see Table 1). But no clear evidence could be found that these thresholds hold to satisfactorily reproduce natural cleaning within PV soiling models (Picotti et al., 2018).

Reference	Precipitation threshold [mm per day]	Comment
Hamond et al., 1997	5	
Kimber et al., 2006	5-10	6 mm as default in pvlib
García et al., 2011	4-5	
Mejia et al. 2013	0.5>	No cleaning for less than 0.5mm
Caron and Littman, 2013	0.5-1	Dependent on soiling level and tilt
Micheli and Muller 2017	0.3	
Coello and Boyle, 2019	1	
Conceição et al. 2020	2.2	2.2 mm has 50% chance to reduce <i>SRatio</i>

Table 1: Threshold for total recovery of reflectivity by rainfall found in literature

3. Experimental Test of State-of-the-Art Models for Natural Cleaning

3.1 Measurement Setup

The here analyzed measurements of the soiling ratio (*SRatio*) have been performed at CIEMAT's PSA in Almería, Spain between December 1st 2018 and June 13th 2021. The daily *SRatio* is derived from a set of two PV reference cells (PVRC, Figure 1) of 50 x 50 mm² monocrystalline silicon covered with a smooth solar glass (Viel, 2017). Both cells are 45° inclined and oriented in South direction. While one cell is cleaned manually week-daily, the other cell has only been cleaned four times during the whole analyzed time period. The temperature corrected *SRatio* is determined according to the IEC 61724-1 standard ("short-circuit current reduction due to soiling", Standard IEC 61724-1:2017) through the measurement of the short-circuit current of the two PVRCs. As the power output of the PVRCs is proportional to the irradiance, the PVRCs *SRatio* is the ratio of the power output of the soiled and the cleaned PVRC. Brightening or dimming events which might have occurred during the investigated period therefore cancel out in the *SRatio* measurements. The *SRatio* is measured at CIEMAT's PSA with a 1-minute resolution.



Figure 1: Two pairs of PV reference cells (PVRC) mounted at CIEMAT's Plataforma Solar de Almería, Spain. The left pair uses textured glass, the right pair smooth glass. The upper row is cleaned and the lower row is soiled. The right pair is used in this study

To derive the daily *SRatio*, the 1-minute resolved measurements are averaged in a 1-hour window around solar noon. Dependencies of the *SRatio* measurements on the solar angle of incidence as discussed e.g. in Wolfertstetter et al. (2021) don't have to be considered in this analysis as only the change due to cleaning is investigated and not the average reduction of the energetic yield. Rain measurements at PSA have been conducted with a Vaisala's Present Weather Detector (PWD52, Vaisala, 2010). 1-minute resolved precipitation measurements are summed-up to daily sums.

3.2 Data analysis

Figure 2 shows the measured daily *SRatios* conducted with the PVRCs at CIEMAT's PSA in Almería, Spain. Further, the *SRatios* modeled with the Kimber model (Kimber et al., 2006) for two different assumed soiling loss rates (*SLR*, 0.0001/d and 0.0002/d) are displayed as an example for a state-of-the-art PV soiling model. Additionally, the daily precipitation sums and maximum daily wind speeds are displayed. The four manual cleaning events during the evaluated time period are marked as red dots. In light blue, the daily *SRatio* measurements which might have been affected by dew have been marked. It was assumed that dew might form if the dew point is surpassed by the ambient temperature by at least 3 K and this state has been present for at least 100-minute values per day.

The Kimber model has been applied using the default values of the Python code library PVlib (Holmgren et al., 2018)

- for the cleaning threshold (daily rainfall acquired to clean the panels, set here to 6 mm)
- the grace period (number of days after a rainfall event when it's assumed that the ground is damp and there is no soiling, set here to 14 days)
- the maximum soiling rate (maximum fraction of energy lost due to soiling, set here to 0.3).

The Kimber model is an empirical model in which the assumed cleaning mechanisms are limited to manual cleaning and cleaning by precipitation. It assumes a constant soiling loss rate (SLR, fraction of energy lost due to one day of soiling) which depends on the geographical region as well as the soiling environment type (Polo et al., 2021). Two different fixed SLR have been tested (0.0001/d and 0.0002/d). The default value for the SLR in PVlib is set to 0.0015, but for the usage of the model in this analysis, the SLR has been adapted. Two values for SLR have been tested to reproduce best the observed soiling loss well, but in many cases they over- or underestimates (especially during the winter months) the actual soiling losses.

The seasonal pattern of soiling which has been observed at several sites (Javed et al., 2021) is better reproduced by this approach during the summer months when less precipitation events occur. Further, it can be seen that the Kimber model does capture some rain induced natural cleaning events like e.g. in summer 2019 or autumn 2020, but misses several soiling rate recoveries which might be caused by light rain events or strong winds (e.g. beginning of 2019 and 2021) which removed deposited particles for the collector surface.



Figure 2: Measured daily *SRatios*, *SRatios* modeled with the Kimber model and two different assumed soiling loss rates, daily rain sums and maximum daily wind speeds at CIEMAT's PSA in Almería, Spain.

To analyze the effect of the natural cleaning, the new parameter "completeness of natural cleaning" is defined. It describes the effectiveness of natural cleaning in dependence of the prevailing soiling levels. It is calculated using

the SRatios measured before and after the cleaning as:

completeness of natural cleaning = $(SRatio_{after cl} - SRatio_{before cl}) / (1 - SRatio_{before cl}).$ (eq. 1)

In other words, the completeness of natural cleaning is the decrease of the soiling loss due to the cleaning divided by the soiling loss before the cleaning. We use the soiling ratios determined the day before the cleaning event and the day after the cleaning for its calculation. Figure 3 displays the completeness of a natural cleaning event in comparison to daily rain sums measured at PSA as well as several thresholds from literature. It can be seen that no unique threshold for rain sums can be defined to describe a complete natural cleaning event. It demonstrates that the threshold-based models do not deliver an acceptable description of the natural cleaning.



Figure 3:Completeness of natural cleaning dependent on the measured daily rain sum at PSA together with several thresholds for complete cleaning from literature. The point size is dependent on the soiling level of the day before the precipitation event (1-SRatiobefore cl).

4. Discussion of Natural Cleaning Mechanisms

The strong deviation of the completeness of cleaning from the threshold assumption of most soiling models seems to be caused by a multitude of physical effects that influence the cleaning apart of the rain sum. The mechanisms for natural cleaning are rather complex and are influenced not only by meteorological parameters like precipitation, temperature, relative humidity, wind and aerosol particle concentration but also by the collector and installation specifications. Due to the complexity of the mechanisms (see also Ilse et al., 2018), simple precipitation threshold models aim to reproduce the natural cleaning behavior only considering the precipitation amount as data for this parameter is often available.

There are several reasons for the observed inaccurate modelling of the completeness of cleaning. It is influenced, for example, by the intensity of the rain, the contaminant properties, the soiling pattern or the collector surface properties. In the following, different effects concerning natural cleaning and the influence of precipitation will be discussed.

4.1 Removal by wind

The natural removal of particles from collector surfaces are mainly driven by precipitation and wind (Picotti et al., 2017). The resuspension of particles by wind is mainly dependent on wind speed and the particle diameter (Nicholson (1993), Ibrahim et al. (2003, 2004), Picotti et al., 2017). Wind can have an important cleaning contribution especially in semi-arid or arid regions where only few precipitations events occur during the course of the year and mainly dust particles contribute to soiling. Wind can cause deposited particles to roll off, slide off or lift off while it has been found that the dominant detachment mechanism for typical particle sizes of dust particles (larger 10 μ m diameter) is rolling off (Roth and Anaya (1980), Ilse et al., 2018). It has been found that particles with smaller diameters are less likely to be removed by wind (Picotti et al., 2017).

4.2 Rain intensity

It can be observed that heavy rain can restore the cleanliness of solar collectors almost entirely, while light rain might

even increase the soiling level of the collector. In this context, not only the daily precipitation sum influences the cleaning effect, but also the rain intensity which is the rate at which the rainfall falls and which is described with the unit mm/h. High precipitation values during a short time period have a stronger cleaning effect than the same amount of precipitation falling on the collector within larger time periods. This can be explained as it is assumed that the cleaning effect is mainly caused by running off rain drops. Is has been observed (e.g. in Blocken and Carmeliet, 2015) that rain drops typically run off after several smaller rain drops accumulated on the surface to a threshold diameter. This diameter is dependent on the tilt of the collector and the weight of the drop, the adhesion force of the collector, the drag force caused by wind and the shear force within the drop (Andre, 2019). Higher rain intensities favor the accumulation of larger rain drops on the surface and therefore also the runoff. Lower rain intensities might induce the remaining and evaporating of smaller rain drops on the surface which can increase the soiling levels of the surface.

4.3 Wet deposition and evaporation

If the force caused by the weight of the drop is exceeded by the other force components, the drop does not run off and is disposed to evaporation. If the rain drops on the collector are evaporating depends on the ambient temperature, the relative humidity, the barometric pressure, the wind speed and rain drop surface and therefore also the shape and the drop volume. While the liquid water component of the drop evaporates, the solid aerosol particles which have been dissolved within the drop remain on the surface and are disposed to mechanisms like cementation or caking. Light rain events which do not induce a drop runoff but only deposit additional particles on the collector surface, therefore further reduce the *SRatio*.

4.4 Dew and soiling pattern

It has been discussed already in several publications that dew is one main driving factor for persistent soiling of solar collectors (e.g. Figgis et al., 2018 or Ilse et al., 2019). Dew enhances **cementation, caking or capillary aging** processes of disposed particles, independent on the particle type (Ilse et al., 2018, Ilse et al., 2019). The resulting increased capillary forces acting on deposited particles therefore reduce e.g. the probability of particle removal by wind or rain. Especially in semi-arid or arid regions, where ambient temperatures drop significantly during nighttime or in coastal regions with high relative humidity, dew formation on solar collectors is an issue as the collector surfaces strongly cementation, caking or aging processes (Ilse et al., 2018) which makes it an important parameter also in the frame of natural cleaning modeling. Further, in few cases dew can also contribute to partial removal of particles from the collector surface by the formation of dew drops running off the collector.

4.5 Particle types and size distribution

Modeling natural cleaning mechanisms, also the particle types and size distribution and therefore the induced different physical and microscopical mechanisms have to be considered. Dependent on the prevailing particle types deposited on the collector surface, the mechanisms of cementing, caking and capillary aging can be more or less progressed. Soluble particles can be taken up from the surface by the rain drops and be therefore washed off. Spherical particles might slide off easier than non-spherical particles. Smaller particles might not be lifted off by wind. Therefore, natural cleaning by impacting rain drops or wind is more or less affective dependent on the present particle types and size distributions.

4.6 Snow

In Cuddihy (1983) it has been stressed that snow can remove particles from collectors when it slides off from a tilted surface. On the contrary, when it melts on the surface, it can even increase soiling losses similar to the effect of dew described before. In the simple natural cleaning models from literature, the effect of snow on dust removal processes has not been considered so far to our knowledge.

4.7 Collector surface properties

The detachment of particles induced by precipitation is dependent on the surface properties of the collector. Particles deposited on smooth surfaces might be removed by lower precipitation amounts due to reduced adhesion forces in comparison to particles on textured surfaces. Several developments to mitigate or reduce soiling of solar collectors have been published (e.g. Guo et al, 2019). In Curtis et al (2019), the authors investigated the effectiveness of rain cleaning on anti-soiling coated collector surfaces in comparison to non-coated collectors. It has been found that the properties of anti-soiling coatings might be more favorable also in terms of collector cleaning by rain. Goossens (2019) showed in wind tunnel experiments, that anti-soiling coated surfaces are cleaned more effectively by lower wind speeds than non-coated or anti-reflective coated surfaces.

4.8 Geometrical considerations

One major influence on the effectiveness of natural cleaning by precipitation is the orientation of the collector and therefore several geometrical effects have to be considered.

One component is the actual precipitation sum which is hitting the collector. The orientation of the collector determines the amount of rain that is intercepted by the collector surface. From geometrical considerations it is clear that the effective rain amount which hits the solar collector is not only depending on the precipitation amount, but also on the wind speed and direction and the orientation of the solar collector. PV and CSP collector surfaces are usually not horizontally mounted and tracked collectors are moving throughout the day. A heavy rain event at times when the collector is facing e.g. down (stow position) or during strong side winds (respectively to the collector position) won't clean the collector the same way as if the rain drops hit the collector perpendicularly.

Additionally, the velocity with which the drops are running off the collector and also the shape of the water stream contribute to the effectiveness of cleaning. The orientation of the collector influences the runoff speed and hence the cleaning effect. Horizontally-oriented collectors have to collect more precipitation to be cleaned completely. The runoff velocity depends not only on the collector orientation, but also on the drop sizes accumulating on the surface and therefore the rain intensity, the adhesion force and the surface properties of the collector as well as the solution processes in which the drop takes up deposited particles.

Further, the force of the hitting drops which is transmitted to the surface has an impact on the removal of deposited particles. This force depends on the drop size distribution, the velocities of the falling drops and the hitting angle.

Some of those influences are discussed in the next subsections to illustrate the possibility to derive such complex parameters.

4.8.1 Effective precipitation intensity

For rain drops falling on the collector surface, the collector surface portion β_{or} (between 0 and 1) perpendicular to the wind direction can be calculated during the rain event according to Wolfertstetter et al. (2019):

$$\beta_{or} = \begin{cases} 0, & for \, \cos \Delta \theta \le 0\\ \cos \Delta \theta * \, \sin \gamma \,, for \, \cos \Delta \theta > 0 \end{cases}$$
(eq. 2)

where γ is the collector's elevation angle and $\Delta \theta$ is the difference between the azimuth wind direction and the mirror azimuth orientation (the vertical wind component is here neglected).

The effective precipitation intensity p_r (in mm which corresponds to liter/m²) can then be calculated with Eq. 3 dependent on the precipitation intensity p and the proportional surface ratio A/B which is hit by falling rain drops (see Figure 4). The surface ratio is dependent on the angle between the normal vector of the solar collector and the rain vector:

$$p_r = p * \beta_{or} * \frac{A}{B} = p * \beta_{or} * \cos(\alpha - (90^\circ - \gamma))$$
(eq. 3)

The collector's tilt is the difference between 90° and α is the distraction angle from a horizontal plane of the rain drop.

The angle α depends on the wind speed and direction. This correlation is also important for e.g. buildings and driving rain on facades. For example, the minimum runoff offset under windows to control the drop impact zone is defined in architecture standards (e.g. in Germany: DIN 18339 or DIN EN 1391-1) and depends on the height of the building (presumably due to assumed larger wind speeds in greater heights). Table 2 and Figure 5 display an experimental correlation between the angular direction of the rain drop and the wind speed according to Schulz (2020) which is inter- and extrapolated up to wind speeds of 25 m/s for this study. With the help of α and Eq. 3, the effective rain sum hitting the solar collector for the site of interest can be derived.



Figure 4: Sketch of rain drops falling on a solar collector.

Table 2: Angular drop falling direction distraction depended on wind speed according to Schulz (2020)

Wind speed [m/s]	Angle distraction from horizontal plane α [°]
3.4	69.30
5.5	58.57
8.0	48.37
17.2	27.62

4.8.2 Drop size distribution and mean drop falling velocity

It can be assumed that the cleaning effect of each rain drop is also dependent on the momentum of the drop transferred to the soiling particles on the collector surface among other influences. The force each drop is introducing on the collector's surface is dependent on the distinct falling velocity, the drop's weight and the angle with which the drop is falling on the surface. To estimate the falling velocity, the drop size distribution during the precipitation event has to be known. Rain drops typically have drop diameters between 0.1 and 6 mm (VDI, 2010). The rain drop size



Figure 5: Inter- and extrapolated assumed distraction angle α dependent on wind speed according to Schulz (2020).

distribution N(D) during a rain event can be derived with the help of the Marshall-Palmer distribution (Marshall and Palmer, 1948). This distribution is dependent on the precipitation sum and the empirical derived constants N_0 which is the number density of rain drops with diameters converging to 0 (equal to 8*103 1/(m³ mm)) and a and b (while a is equal to 4.1 and b is -0.21):

$$N(D) = N_0 \cdot e^{-D \cdot a \cdot R^b}$$
(eq. 4)

R is here the rain rate in mm/h and D is the drop diameter.

The drop falling velocity v_{rd} (in m/s) dependent on the drop diameter *D* (in mm) can then be derived following the empirical approach of Atlas et al. (1973) using measurement data of Gunn and Kinzer (1949):

$$v_{rd}(D) = 9.65 - 10.3 \cdot e^{-6 \cdot D} \tag{eq. 5}$$

The according curve of the calculated rain drop falling velocity v_{rd} dependent on the drop diameter *D* can be seen in Figure 6.



Figure 6: Rain drop falling velocity dependent on rain drop diameter according to Atlas et al. (1973).

The mean drop falling velocity $v_{rd,mean}$ (in m/s) for a precipitation event can then be calculated for the diameter size grid (i=1 to k) according to Eq. 6:

$$v_{rd,mean} = \frac{\sum_{i=1}^{k} N(D)^* v_{rd}(D_i)}{\sum_{i=1}^{k} N(D_i)}$$
(eq. 6)

Figure 7 shows the calculated $v_{rd,mean}$ for the measured precipitation events at CIEMAT's PSA and the assumed rain drop size range between 0.1 and 6 mm. According to literature, mean falling velocities of around 7 m/s have been observed typically for daily precipitation intensities of 2-3 mm (e.g. Marzuki et al. (2013) or Bringi et al. (2018)) which coincides well with the calculation results for CIEMAT's PSA.



Figure 7: Calculated mean drop falling velocities for measured precipitation events at CIEMAT's PSA.

The force transferred to the collector's surface and the soiling particles located on it for every timestep can be calculated with the effective precipitation intensity p_r falling on the collector each timestep (in mm which corresponds to liter/m²), the density of water (corresponding to 1 kg/liter), the mean drop falling velocity $v_{rd,mean}$ (in m/s) and the hitting angle of the drop. It can be assumed that drops hitting the surface in a steeper angle might remove deposited particles easier than drops hitting the surface perpendicularly as a steeper angle might increase the runoff velocity. To fully estimate particle removal by these effects, they have to be integrated in a complete natural cleaning model.

5. Conclusion and Outlook

This study investigates parameters describing the modelling of natural cleaning by precipitation in soiling models for solar collectors. It can be seen, that simplified approaches assuming that the collector is cleaned completely if certain thresholds for the daily rain sum are exceeded do not hold in many cases. The natural cleaning completeness by precipitation depends also on several other parameters like e.g. the intensity of the rain, the soiling levels, the kind of soiling, the collector surface properties, the rain impact direction dependent on the wind speed and the collector orientation. Additionally, it is assumed that the tilt of the solar collector surface the runoff velocity of rain drops and therefore also the cleaning effect. Horizontally-oriented collectors might require more precipitation to be cleaned completely. This geometrical consideration is especially important for the modelling of natural cleaning of tracked collectors as the effective rain sum hitting the collector might change drastically with the orientation of the collector.

In this paper, a detailed discussion of the effect of these parameters and some suggestions to improve the modelling of natural cleaning by rain have been presented. Further insights on the influence of the particle and soiling type on the natural cleaning phenomenon will be investigated with the help of digital cameras. Future work will be the implementation of a complete natural cleaning model which aims to estimate all described removal processes and which can be combined with a soiling model considering dynamic soiling rates.

6. Acknowledgments

This research received funding from the Federal Ministry for Economic Affairs and Energy (BMWi) project "PVOptDigital – Erschließung von 5% Ertragspotential in PV Kraftwerken über optimierte Betriebsführung durch Automatisierung und Digitalisierung sowie optische Inspektionsverfahren" (Förderkennzeichen 03EE1107B).

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Assessing Solar: An Interactive Best Practices Guide to Solar Resource Assessment

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Abstract

Solar energy has become a key technology in the renewable energy transition. Particularly, the decrease in the cost of solar technologies has led to increasing investments and significant penetration into energy systems. This has, in turn, led to a greater need for reliable and accurate solar resource data. Fortunately, there has been a great effort in advancing the state of the art of solar resource assessment, including enhanced solar radiation models and more accurate solar resource datasets. While these research advances are published in great detail in scientific journals, a large gap is left in the path to widespread adoption by the scientific community and industry. The high complexity of these new methods and models often means that they are, in practice, only available to a small group of experts. To that end, *Assessing Solar* presents a practical guide to solar resource assessment using the Python programming language. The guide consists of several sections on different topics, which are organized by theme. Each section provides best practices and includes several examples on how to apply the methods to reallife applications, allowing users to understand the code and, with minimal effort, modify it to fit their own applications. The content is written in the Jupyter Notebook format, allowing for an interactive experience and seamless integration of computational content, figures, equations, text, references, and more. The guide is available at AssessingSolar.org.

Keywords: solar energy, solar resource, Jupyter Notebook, open-source, Python.

1. Introduction

Solar resource data are key in many environmental and energy applications, such as thermal, concentrating, and photovoltaic (PV) solar energy systems. The use of solar resource data ranges from the preliminary design stage, where it is the basis for determining the profitability of economic investments, to the operational stage, where it is used to ensure the correct performance of these systems. Notably, solar PV is at the core of decarbonization policies in the electricity sector and is predicted to become the "king of the world's electricity markets" (International Energy Agency, 2020). Thus, with the increasing development of solar energy projects worldwide, the need for reliable and accurate solar resource data has become ever more important (Sengupta *et al.*, 2021).

Fortunately, the state of the art in solar resource assessment has been significantly advanced in recent years, including improved solar radiation algorithms, down-scaling models, and solar resource datasets with increased spatial and temporal resolution. These new and enhanced methods are usually published in great detail in international scientific journals and specialized conference proceedings. However, the high complexity of these new innovative methods and models often limits their widespread adoption, leaving them only practically available to a small group of researchers and experts. This represents a critical gap in the dissemination of best practices and state-of-the-art methods to the wider research community and industry professionals.

In this paper, we present *Assessing Solar*, a practical guide to solar resource assessment in Python. The guide aims to disseminate solar resource assessment best practices and reduce the barriers that limit users from employing the most suitable and accurate methods. The guide covers a diverse range of topics, each containing a short overview, examples for applying best practices, and recommendations from a group of experts. At the core of

each section is a practical demonstration of the concepts, which uses the Python programming language to demonstrate how the methods can be applied in practice and provide code for users to adopt for their own applications.

The guide is an outcome of the collaborative effort between participants in Task 16 of the International Energy Agency's (IEA) Photovoltaic Power Systems Programme on *Solar Resource for High Penetration and Large-scale Applications*. The guide is publicly available for free at the website *AssessingSolar.org* (AssessingSolar.org, 2021).

The remainder of this paper is structured as follows: Section 2 presents the methodology used in developing the guide, Section 3 introduces the structure of the guide, and Section 4 provides a shortened example from the website. The conclusions and outlook are presented in Section 5.

2. Methodology

Assessing Solar is an open-source community-supported project that provides best practices and practical guidance on solar resource assessment using the Python programming language. The guide has a strong focus on using examples based on real-life applications, making it as relevant as possible to the users.

All of the topics addressed in the guide involve manipulating and modeling solar irradiance data, which is relevant to most users – and less on how to make solar irradiance measurements. Therefore, the majority of the examples deal with applying models using computer code. For this, we have chosen to use Python, as it is very versatile and the most popular programming language for data analysis and visualization (Perkel, 2015). Additionally, Python is open-source and used by most open-source solar-related libraries (Holmgren, 2018), making it the ideal language for this project. Specifically, this guide makes extensive use of the pylib-python library, which provides numerous solar radiation models, is peer-reviewed, and has a well-established contributor base (Holmgren, Hansen and Mikofski, 2018).

A core concept of this guide is to provide practical examples of how to apply models and manipulate data in Python, thus, being able to incorporate computational content was a must. This led to choosing to write the content in the format of Jupyter Notebooks. Jupyter Notebook is a document format that allows interactive computational content integrated together with explanatory text, figures, equations, and references. Jupyter Notebooks have become popular in industry and academic research and are starting to make their way into education. The educational research goals of using Jupyter Notebooks include: (i) the use of a collaborative environment; (ii) self-directed learning; and (iii) an interactive learning environment (Suárez-García *et al.*, 2021). From a developer's perspective, this means that all of the content for a section can be written in a single document, simplifying the writing process and allowing code examples to be at the center. From a user's perspective, it is convenient that each section can be downloaded and executed locally, making the code easily adaptable. Overall, using Jupyter Notebooks allows for an enriched, interactive experience that is not available from traditional word processing software. The individual notebooks of *Assessing Solar* were compiled into a website and a publication-quality book using the Jupyter Book tools (Executable Books Community, 2020).

The majority of users will only interact with the AssessingSolar.org website, where the guide is hosted and the best user experience is achieved. The guide is meant to be continually updated and improved as new methods are developed and more contributors join the community. To facilitate a collaborative experience, the entire project, hereunder the Jupyter Notebooks and website source files, are located in a GitHub repository. This allows anyone to contribute to the guide, raise an issue, or start a discussion. These features were the main reasons for choosing GitHub, which provides free hosting of open-source projects. Using a software development platform offers the additional advantage that every contribution goes through a review process, ensuring that the content is accurate and peer-reviewed. Every time a new contribution has been reviewed and approved, this update will be reflected in a new version of the *Assessing Solar* website within minutes. In this way, unlike the writing of traditional textbooks, the development of *Assessing Solar* is a continuous and dynamic process, where new material can be added quickly.

3. Structure of Assessing Solar

The sections within the guide are organized by themes and cover pre-processing, manipulation, modeling, and analysis of solar resource data. At the time of writing, the guide has four major themes or chapters: (I) solar fundamentals, (II) solar radiation modeling, (III) solar resource data, and (IV) applications.

3.1. Solar fundamentals

The first chapter introduces the fundamentals and basic principles of solar resource assessment, including the components of solar radiation (global, direct, and diffuse radiation), definition of solar angles (azimuth and zenith), and how to calculate the sun position in practice. This chapter also includes a section on how to manipulate solar radiation time-series data, which demonstrates many of the essential Python functions used throughout the rest of the guide. Users or students who are inexperienced with solar radiation data and models are recommended to start with this chapter. More experienced users are urged to go straight to the section that deals with their particular topic of interest.

3.2. Solar radiation modeling

The second chapter covers solar radiation modeling, including algorithms and techniques that are frequently used in solar resource assessment, such as:

- Solar decomposition models, which permits estimating the direct and diffuse irradiation from global horizontal irradiance
- Solar transposition models, which permit estimating the global tilted irradiation, also known as plane-ofarray (POA) irradiance in photovoltaic applications (*planned*)
- Clear-sky radiation models (planned)
- Normalization of solar radiation data, e.g., clear sky index and clearness index (planned)

3.3. Solar resource data

Within the theme of solar resource data, the guide offers guidance on how to retrieve time-series of ground measured and satellite-derived solar irradiance from multiple databases. For example, the subsection titled "BSRN" introduces the Baseline Surface Radiation Network (BSRN), a global network of high-quality solar radiation monitoring stations, and demonstrates how to retrieve and parse data. The function for parsing the BSRN station-to-archive files was developed within this project and contributed to the pvlib-python library.

Additionally, procedures for quality control (QC) of solar data are provided, guiding the user through the process of flagging and removing bad data points. QC is an essential but underprioritized step, where currently, individual users tend to develop their own methods. By providing a reference method, this guide aims to provide users with better, streamlined, and standardized QC procedures while developing a deeper understanding of the potential errors.

3.4. Applications

The applications chapter covers various aspects of applying solar resource data. For example, the section "*Solar Power Modeling*" demonstrates how solar resource data can be used to model the power output of solar photovoltaic systems. A second section covers site adaption, which is the process of using ground measured irradiance data to remove systematic biases in satellite-derived irradiance datasets.

4. An illustrative example of the use of AssessingSolar.org

This section presents an example of how *Assessing Solar* seeks to increase the use of state-of-the-art methods and disseminate best practices. To this end, we have chosen to present the section on decomposition models because it is a good illustration of how the online guide facilitates the application of models from the literature and the handling of in-situ reference data. Decomposition models separate global horizontal irradiance (GHI) into its two components: diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI). The best practices are derived from an extensive study carried out by Gueymard and Ruiz-Arias (2016), where 140 decomposition models were compared to ground measured irradiance data. The study found that the DIRINDEX (Perez *et al.*, 2002) and Engerer2 (Bright and Engerer, 2019) models were the best overall and noted that many popular and frequently cited models did not perform well. Nevertheless, citations in recent years show that the popular but less

accurate models are still widely used.

We believe that the main reasons for the lack of adoption of the more accurate models are the high complexity required for implementing the models and that they remain unknown to many users. This illustrates the two key obstacles that *Assessing Solar* aims to solve: making state-of-the-art models accessible and disseminating best practices to new and experienced users alike.

4.1. Retrieving BSRN solar data

The section on decomposition models starts with demonstrating how to obtain a reference dataset. Reference data is retrieved for one of the high-quality stations in the Baseline Surface Radiation Network (BSRN). In most cases, using data from the BSRN is the best practice, as it is the only network that provides high-quality ground measurements from many different climate zones and continents. However, the BSRN data is stored in a BSRN-specific station-to-archive file format, making accessing the data time-consuming and complicated, a limiting factor for many users. To reduce this barrier, the *Assessing Solar* contributors have developed a standard function for accessing BSRN data from the FTP server or a dedicated THREDDS server using a CF-compliant NetCDF format as part of the *Assessing Solar* framework. The code for accessing the FTP server has been contributed to the pvlib-python library and is available in version 0.9.0 and higher. By having these functions available, users do not have to understand the station-to-archive file format or FTP protocols, but only need to interact with the function documentation and the pvlib-python library. Using the function is then as simple as specifying the inputs: station name, start/end date, and credentials for the BSRN FTP server.

<pre># Retrieving the measurement data df, meta = pvlib.iotools.get_bsrn(station='CAB', start=pd.Timestamp('2021-01-01'), end=pd.Timestamp('2021-07-31'), username=bsrn_username, password=bsrn_username, password=bsrn_password) # Resample the 1-minute data to hourly df = df.resample('lh').mean() # Display six rows of the dataset df['2021-01-01 07':'2021-01-01 12']</pre>							
	ghi	ghi_std	ghi_min	ghi_max	dni	 temp_air	pressure
2021-01-01 07:00:00+00:00	0.600000	0.088333	0.483333	0.700000	1.083333	 -0.190000	1007.200000
2021-01-01 08:00:00+00:00	21.183333	0.206667	20.850000	21.583333	6.550000	 0.891667	1008.000000
2021-01-01 09:00:00+00:00	77.783333	1.036667	76.150000	79.533333	22.183333	 1.846667	1008.000000
2021-01-01 10:00:00+00:00	156.900000	2.688333	152.400000	161.283333	144.450000	 3.618333	1008.000000
2021-01-01 11:00:00+00:00	157.766667	1.931667	154.700000	160.850000	49.983333	 5.143333	1008.000000
2021-01-01 12:00:00+00:00	87.283333	0.646667	86.283333	88.416667	3.050000	 5.228333	1008.000000

Fig. 1: Code example demonstrating how to retrieve BSRN data.

A code example from *Assessing Solar* is presented in Fig. 1, demonstrating how to retrieve data from the Cabauw BSRN station from January to July 2021. For each code example, a copy button is provided in the top right corner to encourage users to use the code and apply it in their own applications.

4.2. Applying decomposition models

The pvlib-python library also provides functions for several different decomposition models. By relying on decomposition models from the pvlib library, users can be confident that the models are implemented correctly, as each code contribution has undergone a rigorous review and testing process. However, the library does not provide guidance on which decomposition model is suitable for a given application, what accuracy can be expected, or how the models differ.

Assessing Solar aims to bridge this gap by introducing and comparing the different models and demonstrating how to use them in practice. For example, in Fig. 2, the DIRINDEX model is introduced and applied in a practical example.



Fig. 2: Screenshot from AssessingSolar.org on how to obtain clear-sky data from CAMS and apply the DIRINDEX model.

The section on decomposition models introduces and applies four different decomposition models, including the DIRINDEX. Subsequently, the output of the models, i.e., a time-series of DNI, is graphically compared to the measured values in Fig. 3.



Fig. 3: Comparison of measured and modeled DNI for one sunny day.

To quantify and compare the performance of the different models, several performance metrics were calculated for each model for the analyzed period. The results showed that the DIRINDEX model outperformed the other models, confirming the findings by Gueymard and Ruiz-Arias (2016). Specifically, the mean bias deviation (MBD) of the DIRINDEX model was -3.5 W/m², whereas the MBD were 41.7, 18.3, and 14.1 W/m² for the DISC, DIRINT, and Erbs models, respectively.

5. Conclusion

This paper has introduced *Assessing Solar*, a practical open-source guide to solar resource assessment. The guide is structured around several themes of solar resource assessment, including topics such as quality control of solar irradiance data, solar radiation data, and how to apply various solar radiation models. The examples illustrated in *Assessing Solar* make use of real data to represent real-life applications, allowing users to learn and directly apply the code and methods to their own applications.

Assessing Solar is a collaborative effort by participants of the IEA PVPS Task 16, and its development is a continuous process as new advances in the field are made. In order to enable the continuous update and expansion of the guide in the future, *Assessing Solar* has been set up in a collaborative manner through an online GitHub repository. The vision for AssessingSolar.org is to become the main online reference for best practices for solar resource assessment.

6. Acknowledgments

The authors would like to thank the members of the IEA PVPS Task 16 for their feedback and ideas during the development of AssessingSolar.org.

Adam R. Jensen would like to acknowledge the financial support of the Danish Energy Agency's Energy Technology Development and Demonstration Program (EUDP) under grant number 64020-1082.

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Assessing the variations in long-term photovoltaic yield prediction due to solar irradiance and module temperature

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Abstract

To mitigate the financial investment risks for PV systems stakeholders, it is a prerequisite to reliably predict the long-term energy yield (LTYP). However, this is not usually the case due to several different influencing effects such as: solar resource, system design, the quality of the components as well as degradation. All these effects increase the uncertainties in LTYP. To improve the prediction accuracy, each of these effects should be separately explored. The main aim of this study is to assess the effects solar irradiance used a representative for LTYP. In the manuscript we show that using multi-years repetition approach that include year-to-year climate variability and solar irradiance brightening/dimming effects reduced the variations to $\pm 2.1\%$. The effect of temperature correction in LTYP model led to variations between $\pm 4.5\%$ in comparison with a nontemperature corrected model but where highly dependent on a given location. Overall, it is shown that for more reliable predictions using the proposed approach, at least 5 years of historical data is needed.

Keywords: Energy yield, solar-irradiance, prediction, PV systems, variations

1. Introduction

A Long-Term Yield Prediction (LTYP) is the estimation of the accumulated total energy production of a defined photovoltaic (PV) system in a given location for a specified period (Reise et al. 2018). For the financial evaluation and planning of PV projects the reliable LTYP is a prerequisite. In principle, different factors affect the accuracy of LTYP by increasing the uncertainty of predicted yield as highlighted in the IEA-PVPS-T13 report (Reise et al. 2018). It is crucial to assess each uncertainty source separately. For example, in (Kaaya and Weiss 2020) the uncertainty due to degradation rate were assessed and shown that using a non-linear yield model with a time dependent degradation rate lowers the LTYP uncertainty. In this study, we add a contribution by assessing the uncertainty due to representative solar irradiance used in LTYP. The typical meteorological year (TMY) data (Cebecaue and Suri 2015) extracted from many years of timeseries data is commonly used as representative input irradiance for LTYP. However, some studies (Ki 2020; Nelken and Żmudzka 2017; Kulesza 2017), have shown that the TMY can lead to under/over-estimation of more than 9% in comparison to Multi-Years timeseries data. The variations are dependent on the location and on the methods for evaluating the TMY. Moreover, the TMY eliminates the year-to-year climate variability. In this study we propose an approach to create representative solar irradiance for LTYP by using irradiance recurrence approach, where historical data is repeated and concatenated into a Multi-Years timeseries that include yearto-year climate variability. Throughout the study, the approach is referred to as "Multi-Years Repetition (MYR)". The motivation of the study is partly fostered by the developing interest to use historical data to predict the remaining useful lifetime and hence the yield of PV systems (Kaaya et al. 2020). Prediction of the energy yield of a PV system is highly influenced by solar irradiance. Although several methods are proposed for irradiance forecast, they are mainly based on short term predictions of several hours, days, weeks, or months ahead. When lifetime energy yield predictions are required, simplifications methods such as the TMY are commonly applied for solar irradiance. However, these methods also require the availability of several timeseries data of almost 10 years which are usually not available specially for ground measurements. Therefore, in this paper we assess if using the proposed MYR approach can provide a solution to lifetime yield prediction using limited timeseries solar irradiance data available. The main objective is to check the consistence of the approach and to evaluate the number of repetitions required to provide more accurate representation of long-term irradiance. This is done by assessing different scenarios and benchmarking them with 30 years irradiance data. Moreover, to check the validity of the proposed approach, six different locations with different climate classifications are used. Given that module temperature is another common factor that affects the yield predictions, in the study, the impact of temperature correction on LTYP model is also assessed.

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2. Methodology

2.1 Mathematical model

In (Kaaya and Ascencio-Vásquez 2021) the different models for photovoltaic power prediction are discussed. The simplest and straight forward to apply are the heuristic models that depend mainly on solar irradiance (G) and in some cases on module temperature. In the same study a non-linear degradation term (second term in eq.1 and eq.2) was integrated to model the lifetime performance. The equations are re-written as:

$$P = \left[x \cdot G + y \cdot G^2 + z \cdot G \cdot \ln^2 \left(\frac{G}{G_{STC}} \right) \right] \cdot \left[1 - exp \left(- \left(\frac{1}{k \cdot t} \right)^{\mu} \right) \right]$$
(eq. 1)

$$P_{T_corr} = \left[\left(x \cdot G + y \cdot G^2 + z \cdot G \cdot ln^2 \left(\frac{G}{G_{STC}} \right) \right) \cdot \left(1 - \gamma \cdot (T_{mod} - 25) \right) \right] \cdot \left[1 - exp \left(- \left(\frac{1}{k \cdot t} \right)^{\mu} \right) \right] \quad (\text{eq. 2})$$

where *P* and P_{T_corr} are the power without and with temperature correction term respectively, *G* is the irradiance, T_{mod} is the module temperature a, b, c, and μ are the model fitting parameters. γ is the temperature coefficient of power in (%/°C) and $G_{STC} = 1000$ w/m². *k* is the degradation rate.

In this exercise a 6050 W PV system is simulated with a 1.3 %/year degradation rate based on a Cadmium telluride (CdTe) PV system in our previous study (Kaaya et al. 2020). The model parameters x = 6.37, y = -0.00040, z = 0.0015 and $\mu = 0.35$ are also based on fitting the above proposed equations to historical data of the same system. To calculate the module temperature, the King model (King et al. 2004) was used as:

$$T_{mod} = T_{amb} + G \cdot \exp(a + b.WS)$$
(eq. 3)

Where T_{amb} is the ambient temperature, WS is the wind speed, a and b are model coefficients.

2.2 Data used

In this study, 30 years (1990-2020) historical weather data (global horizontal irradiance, ambient temperature and wind speed) are extracted from ERA 5 reanalysis (C3S 2017) in six location as shown in Fig.1. The Typical Meteorological Year (*TMY*) of the correspond locations was also extract from PVGIS (JRC 2021). **Tab. 1** shows the different scenarios analyzed in this study, MYR #1, MYR #2, MYR #3 are the MYR scenarios where the historical data is repeated 10, 6 and 2 times respectively and concatenated to get representative of 30 years irradiance data.



Fig. 1: Map showing the locations of the data used in the study. From Nigeria (9.74°, 9.25°), Thailand (14.07°, 100.62°), Turkmenistan (39.78°, 60.21), Slovenia (46.05°, 14.50°), Germany (52.44°, 13.38°) and Russia (55.68°, 37.71°)

Scenario	Corresponding years used	Total number of years
MYT	1990 - 2020	30
TMY	2004 - 2014	10
MYR #1	1990-1993	3
MYR #2	1990-1995	5
MYR #3	1990-2005	15

Tab. 1: Irradiance scenarios used for long-term yield prediction. MYR #1, MYR #2, MYR #3 represents the different Multi-Years Repetition scenarios (years repeated to make a 30 timeseries)

3. Results

The long-term representative solar irradiance is constructed from the three MYR scenarios for all the six locations. Fig.2. for example, shows the long-term constructed timeseries using MYR #1 where 3 years historical data have been repeated 10 times and concatenated for a location in Slovenia. It should be noted that during the concatenation, a shift in time can be observed and therefore should be removed using the appropriate data processing techniques.



Fig. 2: Solar irradiance using MYR #1, where 3 years data are repeated and concatenated to create a 30 years MYT for a location from Slovenia (46.05°, 14.50°). Bold yellow box shows the original data and dashed yellow box show the repetition.

The MYT, the constructed 30 years irradiance using the three MYR scenarios and the TMY are applied in eq.1 to simulate the 30 years power and hence the energy yield. In Fig.3 (A) the simulated annual yield of the different scenarios is presented for a location in Thailand. It is clearly visible that the year-to-year variabilities in yield are eliminated when using the TMY in comparison with other scenarios. The aim was to assess whether these yearly variabilities if considered counterbalance and hence lower the lifetime yield variations. In Fig.3 (B), the corresponding lifetime yield as well as the relative difference in relation to 30 years MYT are presented. In this example it is shown that using MYR approach can improve the LTYP by reducing the relative difference values in comparison to the TMY.

Fig.4 shows the distribution maps of the relative difference values for scenarios MYR #1, MYR #2, MYR #3 and the TMY plotted with increasing years. The values of MYR #1, MYR #2 and TMY become more positive towards increasing years. This was attributed to the solar dimming effect visible in the 30 years MYT (see Fig.5). The lifetime yield evaluated using MYR #3 shows less variations in comparison to MYT since the dimming effect is reduced by this scenario. It was also observed in some location that the relative difference values become more negative towards increasing years which was attributed to solar brightening effect in these locations. Generally, the effect of solar dimming and brightening was more visible with MYR #1 and MYR #2 because in these scenarios few years of historical data are repeated several times and hence these effects are not captured.



Fig. 3: (A) Yearly yield for different scenarios. (B) lifetime yield (30 years) in MWh for the different scenarios and relative difference (in black). The relative difference is evaluated in relation to the 30 years irradiance data (MYT: 1990-2020)



Fig. 4: Distribution maps of relative difference with increasing years for MYR #1, MYR #2, MYR #3 and TMY.



Fig. 5: (A) Extracted trends in long-term irradiance data using the different scenarios. (B) Extracted trend and linear fit in MYT irradiance data showing the solar dimming effect.

Therefore, in locations where solar brightening or dimming is anticipated, a correction to include these effects must be added especially when MYR #1 and MYR #2 scenarios are applied. For example, in this exercise, a linear correction of the irradiance was included as: $(G_{corr} = \delta \cdot t + G)$, where δ is a coefficient that describe the slope due to solar brightening/dimming trend and t is the time in hourly resolution. The coefficient δ is location dependent since brightening/dimming trends varies from location to location. This correction was applied to the proposed MYR approach for all locations. Fig.5(A) and (B) show the relative difference of the simulated lifetime yield using the different scenarios in all the six locations without (A) and with (B) solar

irradiance brightening/dimming correction respectively. The relative difference is calculated in relation to MYT. It is visible that when the correction is considered, the error margin of the 50^{th} percentile reduces (i.e from $\pm 3\%$ to $\pm 2.1\%$). Generally, it can also be deduced that the MYR #3 scenario shows consistently more accurate results in all the six locations according to the relative difference values with and without irradiance correction. However, since for a 30-years lifetime evaluation, scenario MYR #3 means waiting half the PV system lifetime, using MYR #1 and MYR #2 with irradiance correction could be a good option for cases where limited historical data is available. Indeed, it can be concluded from the studied locations that to have good predictions at least 5 years of historical data is needed.



Fig. 6: (A) Relative difference of lifetime yield prediction without solar irradiance correction. (B) Relative difference of lifetime yield prediction with solar irradiance correction. The blue patch shows the 50th percentile of the relative difference values of Thailand (location with highest relative difference)

To assess the effect of temperature correction in LTYP, we applied the models without (eq.1) and with (eq.2) temperature correction term in all the six locations using MYT data. The module temperature was estimated from ambient conditions using the King's model (eq.3). Usually, depending on a given location different model coefficients (a/b) are required to provide good estimations. Therefore, for each location, different values of coefficient were simulated. Using the 50th percentile of the location with maximum errors, the variations in LTYP due to temperature correction are within ± 4.5 % margin. In some locations and with good temperature model coefficients, the effect of temperature correction is negligible as shown in Fig.7.



Fig. 7: Relative difference of lifetime yield prediction with and without temperature correction term. The blue patch shows the 50th percentile of the relative difference values of Thailand (location with highest relative difference)

4. Conclusion

We used different solar irradiance scenarios and data from six different locations to analyze their impact on long-term yield prediction. It is found that using historical data repetition method so-called "**Multi-Years Repetition** (**MYR**)" with year-to-year climate variability could provide better predictions as compared to the TMY which excludes these variabilities. However, to apply this method on few years of timeseries historical data one need to consider the effects of solar brightening or dimming by applying a correction to the generated long-term timeseries. It has been shown that, when the brightening and dimming effects are considered the variations of lifetime yield predictions are reduced from ± 3.0 % to ± 2.1 %. Generally, it has been shown that for the proposed MYR approach, at least 5 years of historical data is needed to have more reliable predictions. Also, in the study, it has been shown that the inclusion of temperature dependency in long-term yield predictions is highly dependent on a given location, in some locations it's significant and in other locations is negligible. Overall, the variations in lifetime yield prediction due to temperature correction is evaluated between ± 4.5 %. We believe these findings will help to improve the reliability of long-term yield prediction especially when limited historical data is available. The irradiance MYR approach can be a useful tool in remaining useful energy yield prediction using ground and system-based irradiance measurements for PV operators.

5. Acknowledgments

We would like to acknowledge and appreciate Dr. Julián Ascencio Vásquez, Senior Solar Performance Engineer, Envision Digital LLC for providing the climate data used in this study.

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Assessment of the Atmospheric Extinction for Solar Tower Power Plants along the Sun Belt: Preliminary Results

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Abstract

Atmospheric extinction between heliostats and receivers has become an important issue in recent years as it limits the amount of useful local solar resource available in large solar power tower plants. Therefore, considering only direct normal solar irradiation in the solar resource assessment for solar power tower plant projects is inadequate and conducts to errors. In this paper, we present preliminary results of the evaluation of heliostat-to-tower atmospheric extinction values along the Sun Belt. The results show that the Atacama Desert in Chile has the lowest values of atmospheric extinction for a 1 km slant range, at around 4%. In general, it is in West Africa, Arabian Peninsula and China where the highest values are found. Chad and Mauritania stand out with 26.4% and 18.8%, respectively. Saudi Arabia and China present values of 16.7% and 16.1%, respectively. Extinction has a direct impact on solar resource assessment and thus on economic studies. Considering local atmospheric extinction values will result in more realistic LCOE values.

Keywords: Atmospheric Extinction, Atmospheric Attenuation, Solar radiation, Solar Spectral Irradiance, Solar Resource Assessment, Solar Tower Power Plants, LCOE, Concentrating Solar Power

1. Introduction

Solar radiation is attenuated as it passes through the Earth's atmosphere due to absorption and scattering processes resulting from the interaction with atmospheric constituents, such as aerosols and water vapour, among others. This phenomenon is known as atmospheric attenuation or atmospheric extinction. The amount of radiation attenuated by the atmosphere increases as the light path and the presence of atmospheric components do. Therefore, atmospheric attenuation maybe particularly strong for long distances in the lower layer of the atmosphere, where the density of these components, or their presence per unit volume, is higher.

Because of this, the solar radiation reflected by heliostats is partially extinguished on its path to the receivers in solar power tower plants (Barbero et al., 2021). A solar power tower plant basically consists of three subsystems: a heliostat field, a receiver, and a tower. The heliostat field is a set of mirrors, called heliostats, which follow the movement of the sun to reflect the solar direct normal irradiance (DNI) onto the receiver at the top of the tower. The receiver absorbs the solar radiation collected by the heliostat field and converts it into process heat at high temperatures. This heat is converted into electricity in the same way as conventional power plants.

Until now, DNI has been considered the key parameter for site selection and design of solar power tower plants. However, atmospheric attenuation limits the amount of local solar resource that can be exploited in solar power tower plants, so that the plant power output is reduced compared to what is expected. This is most noticeable in large plants and when the local climate is heavily loaded with atmospheric aerosols, such as in arid or desert regions. A reduction in solar plant power output can delay the economic recovery of the initial investment for the implementation of solar tower projects, which can lead to project failure.

In a recent study, Marzo et al. (Marzo et al., 2021) have shown that atmospheric extinction plays an important role not only in this phase of solar power tower projects, but also in their economic evaluation (see fig. 1). In their paper, they propose to introduce the atmospheric extinction parameter into the equation for calculating the LCOE(t) for solar power tower plants. By performing a sensitivity analysis of the proposed equation, they calculate the impact of this parameter on the final value of LCOE(t). The result is that the atmospheric extinction parameter can have a high

impact on the LCOE(t) value at locations with an atmospheric extinction of more than 10%.



Fig. 1 Correction to be applied to the levelized cost of energy (LCOE) values if energy losses in solar tower power plants due to atmospheric extinction are considered (Marzo et al., 2021).

Numerous efforts have been made in the last decade to quantify, measure or estimate the atmospheric extinction in solar tower power tower. The methods developed to quantify atmospheric extinction can be classified as: direct measurement methods (Ballestrín et al., 2018, 2016; Goebel et al., 2011; Hanrieder et al., 2015; Sengupta and Wagner, 2012; Tahboub et al., 2012), indirect measurement methods (Barbero et al., 2021; Hanrieder et al., 2012; Navarro et al., 2016) and model estimation methods (Alonso-Montesinos et al., 2020; Ballestrín et al., 2020; Cardemil et al., 2013; Carra et al., n.d.; Hanrieder et al., 2020; Marzo et al., 2021; Mishra et al., 2020; Polo et al., 2016).

Among the direct methods, the CIEMAT-system (Ballestrín et al., 2018) stands out because it has been operating for more than 4 years without failures at Plataforma Solar de Almería (PSA), Spain. CIEMAT-system is based on simultaneous measurements of the grey levels of images of a Lambertian target taken with two cameras 742 m apart. The relevant image processing allows the calculation of the atmospheric transmittance between the two cameras and, consequently, to obtain the extinction values. CIEMAT-system has enabled the development and validation of atmospheric extinction models (Alonso-Montesinos et al., 2020; Ballestrín et al., 2020; Carra et al., n.d.; Marzo et al., 2021; Polo et al., 2016). One of the validated models is the one used to make the world's first atmospheric extinction map, with application to solar tower power plants located in Chile (Marzo et al., 2021).

For the mapping, Marzo et al. developed a methodology based on the analysis of 30 years of historical MERRA-2 atmospheric parameter data at each location. After appropriate data processing, Marzo et al. were able to calculate the solar spectrum at different heights using the LibRadTran radiation transfer code (Emde et al., 2016; Mayer et al., 2020). With this information, the spectral extinction coefficient was obtained for the atmospheric layer of interest. By applying the Lambert-Beer-Bouguer's law, the transmittance and atmospheric extinction were obtained for the different slant ranges found in a 115 MW solar power tower plant, more information in (Marzo et al., 2021).

In this paper we show preliminary results of the application of this methodology to the assessment of heliostat-totower atmospheric extinction in solar tower power plants along the Sun Belt.

2. Materials and methods

The present paper applies the same methodology as the one described in (Marzo et al., 2021). This methodology was validated with the CIEMAT-system at the PSA, Spain, as reported in said reference. This time, the results show the atmospheric extinction for slant ranges of one kilometer considering a 150 m high tower at 14 locations along the Sun Belt. One kilometer and 150 m high is the average heliostat-to-tower distance and the average tower height in a 115 MW power plant, which is a representative power output of today's solar tower power plants.

For the analysis, the Modern-Era Retrospective Analysis for Research and Applications, version 2, also called MERRA-2 (Gelaro et al., 2017), was consulted. MERRA-2 is an atmospheric reanalysis of the Era satellite produced by NASA's Global Modelling and Assimilation Office (GMAO). The model uses a grid resolution of 0.5° latitude and 0.625° longitude. MERRA-2 includes the assembly of aerosol data, providing a reanalysis in which aerosols and meteorological observations are assembled in a global data assembly system.

To have a large representative sample of the atmospheric parameters at each location, MERRA-2 data from the last 30 years, from January 1989 to December 2018, were analyzed for all points studied within the Sun Belt.

The analyzed database includes not only the parameters of interest for the topic of atmospheric extinction, but also those that may be related with atmospheric radiative transmittance and the shape of the solar spectrum: atmospheric pressure at ground level [Pa], relative humidity [%], atmospheric pressure at sea level [Pa], temperature at 2 m [K], ozone [Dobson], precipitable water [kg m⁻²], Ångström parameter [470, 870] nm, total aerosol extinction, aerosol optical thickness (AOT) at 550 nm (τ 550), scattering coefficient of aerosols at 550 nm. The collection of all these data corresponds to step 1 of the methodology diagram in Fig. 2.



Fig. 2 Diagram summarizing the methodology used to estimate the local atmospheric extinction for 1 km slant range. This figure graphically simulates how the extinction affects the radiation, light, travelling through the atmosphere, decreasing the visibility of distant objects, in this case the tower from the observer's point of view, as its effect increases with the distance travelled by the light.

Subsequently, step 2 refers to the data processing to calculate the typical meteorological year (TMY) according to the methodology described in (Wilcox and Marion, 2008).

Once the TMY was calculated, LibRadTran was used to calculate the spectral transmittance values of the vertical column of atmosphere, $T_{\lambda_{-}h}^{\nu}$, from the outer layer to the considered height *h*, at each location and time of TMY. In this case, the altitudes considered for the study were 0 m, ground level, and 150m height, corresponding to the atmospheric transmittances from the outer layer to 0 m ($T_{\lambda_{-}0m}^{\nu}$) and 150 m ($T_{\lambda_{-}150m}^{\nu}$). LibRadTran allows the vertical variability of atmospheric properties to be included. For this purpose, the atmosphere is divided into a series of homogeneous layers, characterized by different optical thicknesses, phase function and single scattering albedo (Marzo et al., 2021). In this paper, the atmosphere defined in the US-standard LibRadTran file was used as input to define the vertical properties of the atmosphere. For the distribution of the aerosol characteristics with height, the aerosol_profile_modtran file was used as input, which linearly distributes the aerosol characteristics up to 6 km (as in the ModTran software) when altitude is non-zero. For a more detailed description of how these files do the distribution of atmospheric properties with height, please refer to (Emde et al., 2016; Mayer et al., 2020).

An intermediate step is multiplying $T_{\lambda_0 m}^{\nu}$ by the extra-terrestrial spectrum it is possible to obtain the spectral direct normal irradiance (DNI_{λ}) at each time of the TMY, which corresponds to an estimate of the solar resource reaching the heliostat under clear sky conditions. This data is reserved for a later step.

From the Lambert-Beer-Bouguer law and the information provided by both spectra, the spectral extinction coefficient for the atmospheric layer between 0 and 150 m was obtained as follows, for further details see (Marzo et al., 2021):

$$\kappa_{\lambda_{\perp}150m} = -\ln\left(\frac{T^{\nu}_{\lambda_{\perp}0m}}{T^{\nu}_{\lambda_{\perp}150m}} * \frac{1}{h}\right) \tag{eq. 1}$$

where $\kappa_{\lambda 150m}$ is the average spectral extinction coefficient, for the atmospheric layer between 0 and 150 m.

Once the spectral extinction coefficient has been calculated, it is possible to calculate the spectral transmittance for 1 km distance, $T_{\lambda}(1km)$, under the local atmospheric conditions described for the calculation of the solar spectra at 0 and 150 m, by using Lambert-Beer-Bouguer's law.
$$T_{\lambda}(1km) = \frac{I_{\lambda,2}}{I_{\lambda,1}} = e^{-\kappa_{\lambda}s}$$
(eq. 2)

Now, it is possible to multiply $T_{\lambda}(1km)$ by the DNI_{λ} at that time of the TMY and the heliostat spectral reflectance, ρ_{λ} , giving the amount of radiation reaching the receiver. Subsequently, the broadband value is calculated, as follows, and averaged for the whole year resulting in an annual mean value of the 1 km slant range transmittance of the place.

$$T(1km) = \frac{\int_{300}^{2500} T_{\lambda}(1km) \rho_{\lambda} DNI_{\lambda} d\lambda}{\int_{300}^{2500} \rho_{\lambda} DNI_{\lambda} d\lambda}$$
(eq. 3)

The average value of the annual atmospheric attenuation for a 1 km slant range, A(1km), is obtained from its definition as follows:

$$A(1km) = 1 - T(1km)$$
 (eq. 4)

For more details and other related calculations see (Marzo et al., 2021).

3. Results

Solar irradiation is a crucial parameter in solar power plant projects using tower technology. This parameter is useful for site selection, solar power plant design and has a great impact on economic studies, such as the levelized cost of electricity (LCOE). However, as explained above, normal direct solar irradiation can be partially extinguished in the heliostat-to-tower path. For this reason, it is inappropriate to evaluate only the direct normal irradiation without considering the atmospheric extinction for the assessment of the solar resource in the framework of solar power tower plants. There is not much information on atmospheric extinction values around the world, except for the locations shown in some specific studies. To get a more global view of atmospheric extinction values, 14 locations around the world were selected.

Figure 3 shows the location of the Sun Belt sites that have been analyzed in this paper. All selected sites are in the Sun Belt. The Sun Belt is the area where the greatest amount of solar radiation is received throughout the year on the Earth. It comprises two bands that encircle the planet. It is located around the tropics of Cancer and Capricorn north and south of the equator. It is in the Sun Belt that most of the world's deserts are located, apart from Antarctica and the Arctic.



Fig. 3 Analyzed locations along the Sun Belt (source: Google Maps).

The high availability of solar resources and the extreme atmospheric conditions of desert environments make the sunbelt an area of interest for analysis in this paper.

The results of the atmospheric extinction calculations for 1 km slant range are shown in table 1. The colour scale indicates the distribution of extinction values, where green indicates the lowest values and red the highest. These values are obtained by applying the methodology described above. Table 1 also shows geographical and climatic information on the sites considered, as well as their elevation from sea level.

				Köppen-Geiger	Elevation	Atmospheric extinction
N°	Latitude	Longitude	Country	Climate Classification*	(m)	for 1km slant range
#1	32.00	-109.38	USA	BSk	1672	5.1%
#2	19.50	-97.50	Mexico	Cfb	2552	5.9%
#3	33.50	-92.50	USA	Cfa	47	7.3%
#4	-24.09	-69.93	Chile	BWk	965	4.0%
#5	19.00	-6.25	Mauritania	BWh	327	18.8%
#6	37.09	-2.36	Spain	BSk	490	6.6%
#7	22.79	5.53	Argelia	BWh	1380	11.1%
#8	-23.56	15.04	Namibia	BWh	409	6.4%
#9	16.00	17.50	Chad	BWh	385	26.4%
#10	24.91	46.41	Saudi Arabia	BWh	755	16.7%
#11	20.50	80.00	India	Aw	226	11.2%
#12	35.50	85.62	China (Tibet)	ET	5254	4.9%
#13	28.00	111.87	China	Cfa	636	16.1%
#14	-12.42	130.89	Australia	Aw	34	8.3%

Table 1: Results of the annual average of atmospheric extinction values for a 1 km slant range for the analyzed locations

* source (Kottek et al., 2006). *Main climates:* A, equatorial; B, arid; C,warm temperate; D, cold continental; E, polar. **Precipitation:** W, desert; S,steppe; f, fully humid; s, summer dry; w, winter dry, m, monsoonal. **Temperature:** h, hot arid, low latitude; k, cold arid, middle latitude; a, hotsummer; b, warm summer; c, cold summer.

The annual extinction values for the sites considered are between 4.0% and 26.4%, corresponding to Chile and Chad, respectively. In other words, the local lower atmosphere causes annual energy losses in solar power tower plants with values between 4% and 26% depending on the place. In general, it can be concluded that atmospheric extinction represents an average of 10.6% of energy losses per year for the stations considered in the study.

The highest annual average values of atmospheric extinction correspond to locations in Mauritania and Chad with 18.8% and 26.4%, respectively. In general, high values (>10%) are found mainly in arid and desert climates (BW), as well as in China (Cfa) and India (Aw). Within arid and desert climates (BW) climates, Chile and Namibia stand out for their low extinction values, 4.0% and 6.4%, respectively.

From these preliminary results, there does not seem to be a relationship between atmospheric extinction and climate type. Thus, for example, it is possible to find the highest and lowest levels of extinction in desert climates (BW), such as in Chad and Chile.

However, it is observed that the highest extinction values coincide with areas where atmospheric aerosol content is high. For example, the Sahara Desert in West Africa, known for its high aerosol content in episodes such as calima, has annual extinction values above 11% in Algeria (BWh), 18.8% in Mauritania (BWh), and 26.4% in Chad (BWh).

High values of aerosol content, linked to anthropogenic factors (Filonchyk et al., 2019), are also found in China and India resulting in extinction values of 16.1% and 11.2%, respectively.

Among the places analyzed, Chile stands out with an extinction value of 4.0% for the Plataforma Solar del Desierto de Atacama (PSDA) at 965 m.a.s.l., and China with a value of 4.9% at 5254 m.a.s.l. near the Tibet region.

Regardless of the magnitude of the extinction values found, it is important to consider atmospheric extinction in the planning and design of solar tower power plants and in economic studies, such as LCOE.

The results shown in this paper cannot be extrapolated to other locations in the country under consideration. They are only taken as an example to show the importance that atmospheric extinction can have in the evaluation of the solar resource in the context of solar power tower plants. To obtain results applicable to different national territories, more in-depth studies, such as the one carried out in (Marzo et al., 2021), should be considered.

However, the results already indicate that the annual DNI value might be insufficient for the assessment of solar tower projects in some locations. Not considering atmospheric extinction losses may lead to an overestimation of solar resource availability and incorrect conclusions in studies related to solar power tower plants.

4. Conclusions

The solar radiation collected by heliostats in solar power tower plants can be partially extinguished depending on the content of atmospheric components and the distance travelled to the receivers on the towers. Atmospheric extinction is a difficult issue to quantify or estimate, which has been studied in the last decade due to the growing concern of the solar industry and investors about the lack of information on the subject.

This paper presents preliminary results of the evaluation of heliostat-to-tower atmospheric extinction values for a 1 km slant range in places sited along the Sun Belt.

The methodology employed is based on the use of long-term model retrieval databases, the LibRadtran radiative transfer code and the application of the Lambert-Beer-Bouguer law. This methodology has already been applied by the authors in a previous work for the elaboration of an atmospheric extinction map in Chilean territory and validated at the Plataforma Solar de Almería, Spain (Marzo et al., 2021).

Overall, the results show that the extinction values are between 4% and 26% for 1000 m slant range for the sites analyzed.

High values (>10%) are found mainly in arid and desert climates. Thus, values of 19% are exceeded in West Africa, even reaching 26% in some places such as Chad. However, Chile stands out globally with values below 4% despite having a desert and arid climate.

These values of atmospheric extinction limit the amount of local useful solar resource available, which has a direct impact on the calculated LCOE values and puts the viability of solar tower power plant projects at risk.

5. Acknowledgments

The authors acknowledge the generous financial support provided by CORFO under the projects (Corporación de Fomento de la Producción) 17BPE3-83761, 13CEI2-21803, 16ENI2-71940 (ING2030) and 7PTECES-75830 under the framework of the project "AtaMoS TeC", and the generous financial support provided by CONICYT under the project ANID/FONDAP/15110019 SERC-Chile. Authors also acknowledgment the financial support of the completed PRESOL project with references ENE2014-59454-C3-1-R1, 2 and 3 with ERDF funds. We are also grateful for the financial support from the Spanish Education and Competitivity Ministry, PVCastSoil project (references ENE2017-83790-C3-1,2,3) and co-financed by the European Regional Development Fund and the Spanish Ministry of Science and Innovation and co-financed by the European Regional Development Fund grant reference PID2020-118239RJ-I00 (MAPVSpain).

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Characterization of solar over-irradiance events in Uruguay

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Abstract

The first characterization of over-irradiance (OI) events in Uruguay is presented. These events are associated to high diffuse and global irradiance and occur during short time intervals for specific sky conditions. Their local characterization is of interest due to their potential impact on solar energy systems. A 1-minute solar irradiance time series with several years of data is used to identify and characterize OI events over one site representative of the broader Pampa Húmeda region. These events were observed in 4.1 % of the filtered data records and the maximum horizontal irradiance was 1601 W/m² (18% above the mean extraterrestrial irradiance). The duration, intensity and seasonality of OI events is analyzed.

Keywords: over-irradiance, solar resource assessment, solar radiation, clear-sky model

1. Introduction

Over-irradiance (OI) events are a short-term phenomenon characterized by a rapid increase of global horizontal irradiance (*G*) above the expected clear sky irradiance. These events can last several minutes and result in global irradiances larger than the irradiance at the top of the atmosphere (TOA). G values exceeding 1400 W/m2, 1650 W/m2, 1634 W/m2 or even 1691 W/m2 have been registered at the 1-minute timescale in different sites as reported by Inman (2016), de Andrade and Tiba (2016), Gueymard (2017) and Castillejos (2020). OI events are also known as cloud-enhancement events, because they occur under partially cloudy conditions and imply an enhancement of the diffuse component of global irradiance, as noted in Gueymard (2017).

The study of OI events is relevant for a proper characterization of the solar resource. For instance, OI events may affect the expected output of a PV power plant causing peaks in the generated power which are difficult to account by forecasting models, as mentioned by Castillejo-Cuberos (2020) and also Järvelä et al. (2020). In solar resource assessment, detecting OI events and treating them differently from the data samples coming from clear-sky conditions or cloudy conditions, can lead to better results in model performance (Gueymard, 2017). In data quality control, it is important to identify OI events, since some filters might mistakenly flag them as invalid samples, when the measured values are actually correct, as noted in Castillejo-Cuberos and Escobar (2020). OI events detection and characterization is also relevant for health risk prevention, in order to prevent the exposure to intense solar UV radiation and its associated negative impacts on human health. Finally,

the frequency and intensity of OI events is relevant in the design of materials which will be exposed to the sun for long time periods, in order to estimate their expected durability under real conditions.

This work presents a first characterization of OI events in a 5-year time series of global horizontal solar irradiance recorded at 1-minute intervals at the main measurement station of the Solar Energy Laboratory (LES <u>http://les.edu.uy</u>) located in Salto, Uruguay, a site that is representative of the broader Pampa Húmeda region. A simple methodology to detect OI events is used, which maximizes the accuracy of OI detections. The chosen methodology is based only on global solar irradiance measurements, so that it can be used later at other sites where only global horizontal irradiance data is available, to analyze the spatial distribution of OI events in the target territory. Several characteristics of the OI events are considered: duration, magnitude, peak intensity and temporal distribution.

2. Data and methodology

2.1 Data

The data used in this work consists of simultaneous records of global (G), direct (G_b) and diffuse horizontal (G_d) irradiance registered at 1-minute intervals at the Solar Energy Laboratory (LES) (latitude 31.27° W, longitude 57.89° S and altitude 56 m a.s.l.). The station is mounted on a Kipp & Zonen SOLYS 2 precision solar tracker fitted with a shading ball assembly and a sun sensor for fine adjustments. The global and diffuse irradiances are measured with class A spectrally flat pyranometers (under ISO 9080:2018 standard) and G_b is measured with a class A CHP1 pyrheliometer. All the instruments are periodically calibrated (every two years, at most) at the laboratory with traceability to the World Radiometric Reference maintained by PMOD/WRC at Davos. The instruments for global and diffuse irradiance are ventilated using standard Kipp & Zonen CV4 heaters/ventilators to avoid problems with dust or water droplets in the domes. These instruments are supervised and maintained at least on a weekly basis.

# diurnal samples	1311947	% of diurnal samples
# samples that pass QC.	962430	disc. 26.6 %
# diurnal samples with solar altitude $> 7^{\circ}$	947015	total disc. 27.8 %
# clear sky samples	397622	selected 30.3 %

Table 1: Filtered samples by quality control procedure (QC) and solar altitude.. On the last column the cumulative percentage of discarded data from the initial set is shown in each step, as the % of selected clear sky data.

The data set corresponds to five years (2016-2020) of continuous monitoring and has been subjected to adequate quality control procedures based on BSRN recommendations by Mc. Arthur (2005), omitting the upper limits so as not to remove possible OI events. Only data with solar altitudes greater than 7° are considered for this analysis, to reduce the impact of

cosine errors. Some OI events with lower solar altitudes may exist but they are associated with low G values and are not the focus of this work. Table 1 shows the number of samples of the initial diurnal data set, and that of the subsets that pass the quality filter and solar height. The percentage of the initial sample discarded in each step is expressed in parentheses.

2.2 Methodology

An accurate detection of OI events is crucial for a proper characterization. Several methods can be used to define and detect OI events, three of which are used by Castillejos-Cuberos (2020). After testing several methods, in this work we identify OI events as those records for which the global irradiance (G) is above the current clear-sky estimate (G_{cs}) by a certain threshold,

$$G > G_{cs} \times (1 + \xi) \tag{eq. 1}$$

where ξ is a positive dimensionless threshold to be determined. This criterion is simple, accurate and is based only on G measurements, so it's scalable to other sites. The determination of the optimum threshold ξ is discussed in detail in the next Subsection. eq. (1) is used in an algorithm for the automatic detection of OI samples in the 1-minute global irradiance time series. Once the set of over-irradiance samples has been determined, its statistics are calculated. The analysis considers the relevant characteristics of 1-minute OI samples but also of consecutive over-irradiance periods or OI events (OIE), as described in the following Subsection.

2.3 Over Irradiance detection

A clear-sky model is required for the identification of OIE from eq. (1). In this work, the ESRA clear-sky model (Rigollier 2000) is used. This model uses the Linke Turbidity (T_L) as its single atmospheric parameter and it can be accurate over the region of interest, when used with locally derived cycles of daily mean T_L , as studied in Laguarda and Abal (2017), Laguarda et al. (2020). Additional validation of the model, including the one done for this work, is described below. The model is based on average atmospheric information and in particular it is not sensitive to small intra-day variations in the atmosphere. However, it is simple and adequate for the purposes of OI sample detection.

Clear-sky model validation

The ESRA model (with local T_L cycles) has been validated over the region in (Laguarda et al., 2021) at the hourly timescale using clear-sky irradiance measurements from several sites, including the one considered in this work.

The metrics used in the validation are the usual relative Mean Bias Deviation (rMBD) and the relative Root Mean Square Deviation (rRMSD), both expressed as a % of the

measurement mean. Additionally, the Kolmogorov-Smirnov Integral (KSI), which measures the distance between the cumulative probability of the estimated and the reference series, is calculated. See Laguarda and Abal (2017) or Gueymard (2014) for detailed definitions and examples of their usage in the solar resource assessment context.

The hourly validation done in (Laguarda et al., 2021) for the site considered in this work was performed using a standard random sampling and cross-validation process and shows a negative rMBD of -0.2%, rRMSD of 2.9% and a KSI of 5.2 Wh/m². For this work, a new validation was done at the 1-minute timescale, with the results listed in Table 2 below. The clear sky samples were selected using the method described in Reno et al. (2016), imposing strict thresholds to avoid false positives. In order to remove a potential dependence of the OI characterization's results with the clear sky model chosen, a standard linear site adaptation, as described by Polo (2016), was applied to the raw ESRA estimates. This procedure results in an unbiased version with an rRMSD of 3.5% (see Table 2), which is similar to the instrument's uncertainty for 1-minute records. The site-adapted ESRA will be used from here on as the clear-sky model.

	original (%)	site adapted (%)		
rMBD (%)	-3.8	0.0		
rRMSD (%)	5.2	3.5		
KSI (W/m ²)	23.6	17.1		
% relative to the average of 397622 clear sky measurements = 624.6 W/m^2				

Tab.2: Performance of original and site adapted GHI estimates of ESRA clear sky model implemented for this work.

Determination of the threshold ξ

As stated in eq. (1), a global irradiance measurement is considered OI when it exceeds the site-adapted clear-sky model by a coefficient $1+\xi$ so a proper choice of the threshold ξ is essential for accurate results. Low values of ξ enhance the chance of incorrectly tagging clear sky samples as OI (false positives). On the other hand, high ξ values will select only a subset of the real OI events (false negatives). The optimum value for ξ must be determined from the data and visual inspection by a careful analysis.

The fraction of selected clear sky samples that *are not tagged as OI* is shown in Fig. 1, in terms of ξ . In order to balance this two effects, we impose $\xi = 0.105$, which equals 3 standard deviations (as estimated from the ESRA model uncertainty, i.e. P99 confidence level for a normal distribution of the residuals). Figure 1 shows that for $\xi = 0.105$ less than 1% of the detected clear sky samples are tagged as OI. This is a rather restrictive test as compared, for instance, with (Castillejos-Cuberos, 2020) which uses a 1.05 as a threshold

($\xi = 0.05$), but it reduces the chances of incorrect OI identification, as confirmed by visual inspection of several OI samples.

Selection of OI events

After an initial step with $\xi = 0.105$, a few clear-sky samples are still erroneously identified as OI events. Thus, in a second iteration, the few clear sky samples incorrectly selected as OI are removed using the clear sky detection algorithm provided by PVlib by Holmgren (2018) based on the criteria described in Reno (2016).



Fig. 1: Fraction (%) of clear sky samples not tagged as OI versus ξ .

This algorithm identifies 2.7 % of the OI pre-selected samples as clear-sky and these are removed, under the assumption that there is no over irradiance under clear sky conditions.

The results of the previously described OI selection algorithm are summarized in the diagram of diffuse fraction ($f_d = G_d/G$) vs. clearness index ($k_t = G/G_{toa}$, where G_{toa} is the global horizontal irradiance at the top of the atmosphere) shown in Fig. 2. This figure includes all the measurements that passed the quality control procedure as gray dots. The records identified as OI events are shown in orange and the clear sky samples are colored in light blue. Note that none of the OI samples are tagged as clear-sky.

As an example of the OI selection procedure, Fig. 3 shows the measured global (gray) and diffuse (green) together with the clear-sky estimate for one specific day, January 28 of 2020. The OI threshold is shown as a dashed brown curve and the clear-sky estimates as light blue dots. The threshold must be chosen large enough so as to avoid erroneous identification of low sun (early morning, late afternoon), clear-sky samples as OI.

2.4 Characterization of OI and OIE

An exploratory study of the selected OI's is carried out through the analysis of some of its quantifiable properties, such as intensity (irradiance value) or its frequency of occurrence. Then, we focus on the characteristics of consecutive OI events (OIE), which also have a duration (Δ , in minutes), a magnitude, *M*, defined as

$$M = \int_{t}^{t+\Delta} G \, dt \tag{eq. 2}$$

which has units of energy density (J/m^2) and a maximum or peak intensity (PI). The seasonal behavior of these characteristics is studied, as well as the occurrence distribution within a day.



Fig. 2: Diffuse fraction (f_d) vs clearness index (k_t) diagram for the quality-checked data (shown in gray). The light blue dots indicate clear sky samples and the orange dots identify OI samples.



Fig.3: Example of OI detection on a time series (28/01/2020).

3. OI statistics

The OI selection procedure selects 4.2 % of the 947015 valid samples as over-irradiance. The yearly percentage of OI samples varies between 3.0 % and 4.8 % of the data in each year between 2016 and 2020, as shown in Table 3. As auxiliary information, the table presents the percentage of data which surpasses the solar horizontal irradiance at the Top Of the Atmosphere (TOA), defined as $G_{TOA} = 1361 W/m^2 \times F_n \times cos(z)$, where z is the solar zenith angle and F_n is the orbital correction factor for day n. As expected, these samples are much rarer and are usually below 0.2 % of the total samples in each year.

Seasonal dependence is evaluated by checking the maximum values of OI registered in each season-year. For each maximum, the relative amount by which the irradiance at TOA is exceeded is indicated between parentheses. The OI subset has a maximum G of 1601 W/m² (which is 16.4 % above G_{TOA}) observed during January 2017. The maximums per year show more dispersion, ranging from 2 % to 16 % in excess of the average TOA horizontal irradiance. A similar range of values (between 1400 and 1691 W/m²) has been reported in Inman et al. (2016), De Andrade and Tiba (2016), Gueymard (2017), Castillejo-Cuberos (2020).

OIE analysis

Grouping the samples in consecutive series of OI (OIE) allows us to study the typical durations of cloud-enhancements events, as well as their magnitude in terms of accumulated energy. Figure 4 shows an histogram of the durations of OIE's. In 95% of the cases, Δ is less than 10 minutes. The behavior of Δ is quite stable between years, with small seasonal variations in the P95 duration (in minutes): 10 in summer, 12 in autumn, 8 in winter and 9 in spring.

	YEAR	2016	2017	2018	2019	2020
# of selected OI	samples (%)	4.7	4.1	4.9	4.5	3.0
# of OI samples a horizontal TOA	above (%)	0.19	0.23	0.19	0.16	0.10
# valid data		178934	208030	173885	167910	218256
	summer	1461 (8.04 %)	1601 (16.4 %)	1435 (4.16 %)	1533 (10.8 %)	1510 (10.3 %)
Maximum in W/m ²	autumn	1209 (4.61 %)	1269 (11.8 %)	1225 (9.28 %)	1147 (1.83 %)	1106 (3.91 %)
(% above G _{TOA}).	winter	1267 (14.2 %)	1239 (16.4 %)	1177 (12.9 %)	1164 (6.95 %)	1247 (16.9 %)
	spring	1557 (15.1 %)	1522 (10.8 %)	1443 (1.96 %)	1421 (2.85 %)	1433 (3.46 %)

Table 3: Characteristics of	of Ol's	by season	and year.

These results, detailed by season and year, as well as the number of OIE registered can be found in Table 4. As expected, the maximum number of OIE's occurs in summer and the maximum typical duration (around 12 minutes) tends to occur in Autumn.

The magnitude (or energy density) associated with an OIE, M, is obtained from eq. (2). Seasonal histograms for M are shown in Figure 5. The figure includes the mean and the P95 magnitudes in each case. At a qualitative level, the 4 the distributions are similar. At a quantitative level, as expected, the most energetic events (both on average and in P95) occur in summer, they are moderate and similar in autumn and spring, and they are less energetic in winter. As a reference, a 5 minute OIE at constant irradiance of 1000 W/m² represents a magnitude of 300 kJ/m².



Fig 4: Histogram of Δ (min). The P95 duration is 10 minutes (vertical line).

	YEAR	2016	2017	2018	2019	2020
Number or OIE	summer	771	1185	836	1133	800
	autumn	649	828	685	630	464
	winter	439	301	497	216	260
	spring	927	629	640	445	492
	summer	10	11	11	10	10
Δ at P95 (minutes)	autumn	12	10	13	12	11
	winter	8	7	8	9	10
	spring	9	9	9	8	10

 Table 4: Number of OIE and its P95 duration by season and year. The year in which each variable records a maximum is highlighted in gray.

The seasonal distribution of peak intensities (PI) of the OIEs (as well as its mean and P95 values) are shown in Figure 6. The PI distribution shows differences throughout the year. The events with the highest intensity peaks occur in both spring and summer, with mean values greater than 900 W/m² and P95 values of 1300 W/m². These values are slightly larger in spring. In autumn and winter these values are similar and decrease to approximately 660 W/m² (mean) and 1030 W/m² (P95), with slightly higher values for winter.



Figure 5: Histograms of Magnitude (in kJ/m2) of OIE, classified by seasons. The vertical axis is in logarithmic scale.

Finally, in addition to the seasonal dependence, we also analyze at what time of day OIE's are most likely to occur. Figure 7 shows the OIE's on a solar diagram (solar altitude vs. solar azimuth angles). Brighter colors indicate more occurences of OIE's. For winter and autumn (lower region of the diagram), the OIE's occur mainly around noon with a small trend towards the afternoon (West). In the upper region, related to spring and summer, the occurrences are more smoothly distributed with a greater presence in the regions with azimuth greater than 50° or less than -50°, that is, associated with the morning and afternoon. The behavior is almost symmetrical with a greater number of occurrences towards the afternoon.



800 1620 Intensity (W/m^2)

a. Summer, mean = 923 W/m², P95 = 1299 W/m²





c. Winter, mean = 672 W/m², P95 = 1037 W/m²



Figure 6: Histograms of Peak Intensity (in W/m2) of OIE, classified by seasons.



Figure 7: Over-irradiance occurrences on a Solar diagram (solar altitude vs solar azimuth). The colors indicate the number of OIE occurrences. Azimuth is zero when looking at the equator and positive in the morning.

4. Conclusions

A first analysis of solar over-irradiance events was performed using 5 years of 1-minute data for a site in Uruguay which is representative of the broader Pampa Húmeda region. Individual samples were identified as over-irradiances (OI), based on the comparison of the GHI measurement with the clear sky estimate from an unbiased clear-sky global irradiance model. The optimal threshold factor for this method was determined. Over-irradiance events (OIE) are frequent throughout the year and represent, on average, 4.3 % of the validated data samples. The duration of these events is typically less than 10 minutes (P95), with the largest durations taking place in autumn.

The average magnitude of these events follows a clear seasonal trend: the most energetic events occur in Summer (mean of 165 kJ/m²) and the least energetic in Winter (103 kJ/m²), while during Autumn or Spring they have intermediate magnitudes (130 kJ/m²). Peak intensities of OIE's are distributed according to a different pattern. The mean intensity peaks in Summer and Spring are similar (over 900 W/m²), as are those in autumn and winter (over 650 W/m²). However, the maximum intensity peaks (P95) are slightly greater in spring than in summer (1308 and 1299 W/m², respectively) and greater in winter than in autumn (1037 and 1022 W/m², respectively) although these differences are hardly significant. The daily distribution of OIE's has been analyzed and the OIE's in winter and autumn occur mainly around solar noon and in the early afternoon. In spring and summer, OIE's mostly occur with lower solar heights, especially in the afternoon. However, it should be noted that a 7° lower threshold has been applied to the solar data.

As future work, cloud information from sky cameras can be incorporated to correlate the selected OI samples with different types of clouds. Access to sky camera information will also allow detecting measurements with water drops at the sensor dome, which are frequent under low-sun conditions and can be incorrectly selected by the automatic algorithm as cloud enhancement. Consideration of other available variables, such as direct or diffuse irradiance, UVA and UVB measurements and pyrgeometer infrared (3 - 30 μ m) sky irradiance will improve characterization of sky conditions associated to OIE's. Other clear sky models can be used for detection of OI (including satellite based ones, such as Mc Clear) in order to check the robustness of these results.

Finally, because the proposed detection method only requires GHI, its application can be generalized to other regional radiometric stations that only record that variable with 1-minute time intervals. This will allow the characterization of the spatial distribution of OIE's and their variability over a broader area.

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An Assessment of and Access to NASA CERES Hourly Solar Irradiance Data Products Using POWER Web Services

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Abstract

The NASA Prediction Of Worldwide Energy Resources (POWER) project targets three user communities: Renewable Energies (RE), Sustainable Buildings (SB), Agroclimatology (AG). The Clouds and the Earth's Radiant Energy System (CERES) SYN1deg (Ed4.1) hourly all-sky global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI), which span from March 2000 to within a few months of real time, are now the source data provided through POWER Web Services Suite (WSS). Although the SYN1deg (Ed4.1) hourly DHI and direct horizontal irradiance (DirHI) sum to the GHI that agree reasonably well with matching Baseline Surface Radiation Network (BSRN) measurements, the DHI and DirHI components show appreciable positive and negative biases, respectively, relative to the BSRN data. The direct normal irradiance (DNI) derived by dividing the DirHI by the cosine of the solar zenith angle $[\cos(Z)]$ is, therefore, also appreciably biased relative to the BSRN data. In this report, we present a simple bias-based correction scheme. We perform the correction in the following procedure: 1) Correct the GHI and DHI according to the biases that are expressed as functions of cos(Z); 2) Compute the GHI-DHI difference to get the corrected DirHI; 3) Divide the corrected DirHI by cos(Z) to get the DNI. In addition, when Z is larger than 75°, the derived DNI can sometimes become unrealistically large as $\cos(Z)$ approaches 0 without considering refraction effects. We correct the $\cos(Z)$ by adding a linear component to it to prevent cos(Z) from becoming infinitesimally small. The results from the scheme agree better with the BSRN than that from the DirIndex model.

Keywords: POWER, CERES SYN1deg, Diffuse horizontal irradiance, Direct horizontal irradiance, Direct normal irradiance, Bias-based correction

1 Introduction

The NASA POWER surface meteorology and solar energy Version 6.0 (SSE V6.0) database is being superseded by the one based on the CERES SYN1deg (Ed4.1) hourly data. The SSE V6.0 dataset was derived from the NASA GEWEX SRB Release 3.0 monthly mean solar GHI and DHI that were derived from 3-hourly means spanning the time from July 1983 to December 2007. The method for deriving the monthly mean DNI was based on the regression analysis of the BSRN data that cover the years from 1992 to 2005, and the details of the regression analysis are available in Appendix A in Zhang et al. (2014). The monthly mean solar irradiance on surfaces tilted equatorward at various angles were derived using the method of Liu and Jordan (1960), the isotropic model (Duffie and Beckman, 2013) and the monthly average day (Klein, 1977).

Zhang et al. (2014) applied the DirIndex model to the GEWEX SRB Release 3.0 3-hourly GHI, and the resulting monthly mean DNI agree with the BSRN data better than those of SSE V6.0. The DirIndex model requires input of hourly all-sky and clear-sky GHI, surface pressure, sea-level pressure, aerosol optical depth (AOD) at 700 nm, atmospheric column water vapor and elevation angle of the Sun. So it is an overstretch of the model to apply it to 3-hourly data. Part of the reason that the model was applied to only the 6 years from 2000 to 2005 was that, at that time, the AOD data were available for only those 6 years.

The CERES SYN1deg (Ed4.1) hourly solar irradiance dataset start from March 2000 and span to near present (Loeb et al., 2018; Rose et al., 2013; Rutan et al., 2015). In addition to GHI, the dataset also provides hourly DHI and direct horizontal irradiance (DirHI) along with hourly solar zenith angle (Z) which is derived such that the top-of-atmosphere hourly DirHI divided by cos(Z) is equal to the solar constant. The surface hourly DNI is then derived by dividing the hourly DirHI by cos(Z), namely DirHI/cos(Z), and the daily and monthly mean DNI are computed by arithmetically averaging the hourly DNI. Comparison with the BSRN data show, however, that the DNI derived as such are significantly negatively biased against the BSRN data. Further investigations show that the SYN1deg (Ed4.1) DHI are significantly positively biased against the BSRN while the DirHI are significantly negatively biased against the BSRN while the DirHI are significantly negatively biased against the BSRN while the BSRN data, agree with the BSRN fairly well.

We then applied the DirIndex model to the SYN1deg (Ed4.1) hourly GHI to derive the hourly, daily and monthly mean DNI and compared the results with BSRN. It was found that, although the DNI computed from the original SYN1deg (Ed4.1) data and simple division, namely, DirHI/cos(Z), are significantly biased against the BSRN, the uncertainty as represented by the root-mean-square error and standard deviation is much smaller than that of the results from the DirIndex model. In addition, we analyzed the biases of DHI and DirHI as functions of $\cos(Z)$, and found both exhibit simple, near-linear relation with $\cos(Z)$. This suggests to us that a simple bias-based correction according to $\cos(Z)$ can provide results better than that from the DirIndex model. In other words, this scheme can produce a dataset that is not only less biased but depicts the spatiotemporal variability better.

To be specific, the correction scheme is as follows: 1) Correct the GHI; 2) Correct the DHI; 3) Compute the corrected DirHI by subtracting result from Step 2) from result from Step 1); 4) Divide results from Step 3) by cos(Z) to get the corrected DNI.

In Section 2, the details of the bias-based correction will be given; in Section 3, the original CERES SYN1deg (Ed4.1) adjusted hourly GHI, DHI, DirHI and the derived DHI, or DirHI/cos(Z), will be compared with their BSRN counterparts; in Section 4, the corrected version will be presented; the conclusions will be given in Section 5.

2 The Solar Irradiance Data Based on the CERES SYN1deg (Ed4.1)

The Clouds and the Earth's Radiant Energy System (CERES) Mission flies instruments on multiple platforms to measure and monitor the Earth's Radiation Budget and its variability (Wielicki et al., 1996; Loeb et al, 2016). One of the CERES data products provides both the top-of-atmosphere and surface radiative fluxes, but using a radiative transfer model, together with Geosynchronous satellite observations and multiple ancillary inputs to compute the surface radiative fluxes (Rose et al., 2013; Rutan et al., 2015) globally gridded to 1°x1° resolution. This product, called the SYN1deg (Ed4.1), provides estimates of the surface hourly solar irradiance data spanning the period from March 2000 to within a few months of near present time and are now the source data for the POWER Web Services Suite (WSS). Two versions of the CERES SYN1deg (Ed4.1) hourly irradiances are available, the initial and adjusted. Based on comparisons with the BSRN data, we found that the "adjusted" GHI agree somewhat better with the BSRN than the initial one. The overall bias/ σ of the adjusted version are -2.91/83.44 W m⁻² and of the initial version are -4.51/82.44 W m⁻² where σ stands for standard deviation; in a 20-bin analysis of the cos(Z), we found that except in a few extreme bins, the adjusted version is slightly better than the initial version in most of the bins. So we decided to use the adjusted version. Henceforth, all SYN1deg data refer to the adjusted version. Beside the hourly global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI), the POWER WSS derives the direct normal irradiance (DNI) by dividing the direct horizontal irradiance (DirHI) by the cosine of the solar zenith angle [cos(Z)], namely, DirHI/cos(Z). However, we found that, although the original SYN1deg (Ed4.1) DHI and DirHI sum to the GHI that agree reasonably well with the Baseline Surface Radiation Network (BSRN) data, the DHI and DirHI show appreciable positive and negative biases, respectively, against the BSRN data and, therefore, the derived DNI, or DirHI/cos(Z) also show significant biases against the BSRN data. To be precise, the overall bias/ σ of the DHI are 30.58 W m⁻², and in the 20 bins of cos(Z), the bias increases steadily from -2.29 to 116.22 W m⁻², or from -21.78% to 41.75% of the mean BSRN DHI; the overall bias/ σ of the DirHI are -37.09/116.48 W m⁻², and in the 20 bins of cos(Z), the bias changes from -2.18 to -90.40 W m⁻², or from -45.54% to -16.64% of the mean BSRN DirHI; the overall bias/ σ of the derived DNI, or DirHI/cos(Z), are -54.32/196.35 W m⁻², and in the 20 bins of cos(Z) goes from 40.17 to -93.94 W m⁻², or from 89.97% to -16.79% of the mean BSRN DNI (Oumura et al., 1998).

So we decided to make a correction of the data. We have previously applied the DirIndex model to the GEWEX SRB GSW(V3.0) 3-hourly GHI to derive the 3-hourly DNI (Zhang et al., 2014; Ineichen, 2008), since the solar energy community is particularly interested in the DNI. The DirIndex model requires the inputs of the all-sky and clear-sky GHI along with surface pressure, aerosol optical depth at 700 nm, the atmospheric water vapor and so on. The DirIndex model is (Gueymard and Ruiz-Arias, 2016). More recently, we applied the DirIndex model to the CERES SYN1deg (Ed4.0) hourly data to get the SYN1deg-based hourly DNI (Zhang et al. 2017), and the overall bias/ σ are found to be 8.54/228.81 W m⁻². The σ , or standard deviation, represents the magnitude of uncertainty, and this σ is about 17% larger than that of the DNI derived from the original SYN1deg (Ed4.1) DirHI, or DirHI/cos(Z). This implies that the DNI derived from the original SYN1deg (Ed4.1) hourly DirHI, albeit significantly biased in a systemic way, captures the spatiotemporal variability of the DNI than the DirIndex model does, and in addition, it is possible to perform a simple bias-based correction to get a set of DNI with a smaller uncertainty than that of the DirIndex model.

3 Comparison of the original CERES SYN1deg (Ed4.1) hourly irradiances with BSRN

Figs. 1-3 show the comparison of the original CERES SYN1deg (Ed4.1) hourly GHI, DHI, and DNI, or DirHI/cos(Z), with their respective BSRN counterparts. The hourly DirHI, which is biased on the opposite side of DHI at the same magnitude, is not shown due to limited space.

In terms of the overall statistics, the GHI agree with the BSRN reasonably well. In most of the 20 bins of the $\cos(Z)$, the biases are negative; in the five bins approaching the zenith, or the overhead position of the Sun, the biases are positive, and in the last bin, the bias maximizes at 24.04 W m⁻². The DHI, on the other hand, shows a positive overall bias of a significant magnitude, and in the 20 bins of $\cos(Z)$, the bias shows an unmistakable near-linear increasing trend on both the absolute and relative scales as shown in Fig. 2c-d. The DirHI, not shown here due to limited space, is biased equally significantly, though on the opposite side of DHI, because DirHI and DHI sum to GHI which agrees with the BSRN reasonably well. For this reason, the derived DNI, or DirHI/cos(Z), shows notable biases in the bins of $\cos(Z)$. The GHI, DHI, DirHI and DNI comparison statistics are summarized in Table 1.

The unambiguous near-linear pattern of the biases of DHI and DirHI in the bins of cos(Z) suggest that the biases are not just stochastic, but might be systemic, or deterministic. In addition, although the overall bias of DNI is considerable, the σ , or standard deviation, that represents the uncertainty of DNI, is still appreciably smaller than the DNI from the DirIndex model. These facts suggest that a simple bias-based correction can produce a set of DNI with an uncertainty smaller than that from the DirIndex model.

All-Sky Hourly	Bias	RMS	Р	σ	μ_{DATA}	Ν	
Original CERES SYN1deg (Ed4.1)							
GHI	-2.91	83.49	0.9566	83.44	341.63	3,331,148	
DHI	30.58	85.86	0.8306	80.23	168.33	3,450,473	
DirHI	-37.09	122.24	0.8881	116.48	192.60	3,009,959	
DNI, or DirHI/cos(Z)	-54.32	203.73	0.8224	196.35	342.79	3,009,963	
		After Co	rrection				
GHI	0.01	83.19	0.9567	83.19	344.54	3,331,148	
DHI	0.01	65.70	0.8300	65.70	137.88	3,450,473	
DirHI, or GHI-DHI	-0.02	106.45	0.9058	106.45	222.64	3,107,945	
DNI, or DirHI/cos(Z)	0.72	182.15	0.8509	182.15	386.06	3,107,969	
DNI from the DirIndex Model							
DNI from DirIndex Model ^{*1}	8.54	228.81	0.7580	228.65	444.91	2,195,000	

Table 1. CERES SYN1deg (ED4.1)-BSRN hourly all-sky GHI, DHI, DirHI and DNI comparison statistics from 2000-03 to 2020-07 before and after the correction. The DNI from the DirIndex model in the last line for comparison.

*1. The DNI from the DirIndex model covers the period from 2000-04 to 2016-12 only.



Fig. 1. Comparison of the *original* CERES SYN1deg (Ed4.1) hourly GHI with the BSRN data from 2000-03 to 2020-07. a) The scatter density of the hourly GHI. The statistics shown are categorized as "Global" that includes all data points, "60° Poleward" and "60° Equatorward"; ρ stands for correlation coefficient, ρ standard deviation, μ_{BSRN} the BSRN mean, and N the total number of data points. b) Histogram of the SYN1deg (Ed4.1)-BSRN hourly GHI differences. c) and d) The biases in 20 bins of cos(Z) on absolute and relative scale, respectively. e) and f) The bias, σ and p on a site-by-site basis.



Fig. 2. Same as Fig. 1 except for DHI.



Fig. 3. Same as Fig. 1 except for DNI, or DirHI/cos(Z).

4 The Correction Methodology

4.1 The bias correction

The bias-based correction scheme is as follows: 1) Apply the bias-based correction to the DHI and GHI as well; 2) Subtract the DHI from the GHI to get a corrected version of DirHI; 3) Divide the DirHI by cos(Z) to get DNI. Note that the hourly solar zenith angle, Z, is part of the CERES SYN1deg (Ed4.1) data, and it is determined such that the top-of-atmosphere (TOA) DirHI divided by the cos(Z) is equal to the solar constant.

To perform the correction of DHI, the SYN1deg-BSRN hourly DHI biases are first calculated in 100 bins of $\cos(Z)$, as opposed to 20 bins in Figs. 1-3. In each bin, the bias is calculated on the absolute scale, *Bias*, in W m⁻², and on relative scale, R_{Bias} as percentage of the mean SYN1deg (Ed4.1) hourly DHI, as opposed to the BSRN hourly mean DHI, the bias is considered to represent the center of the bin. Now both *Bias* and R_{Bias} are functions of $\cos(Z)$. For any given hourly DHI, I_{DH} , its corresponding $\cos(Z)$ is first used to determine its bias through linear interpolation; if the *Bias* or R_{Bias} is negative, then the corrected DHI, $I_{DH}^c = I_{DH} - Bias$; if the the *Bias* or R_{Bias} is positive, then the corrected DHI, $I_{DH}^c = I_{DH} \cdot (1 - R_{Bias})$. The scheme keeps or reduces the random variability of the original data.

The correction of GHI is similarly performed. The difference between the corrected GHI and corrected DHI is the corrected DirHI.

4.2 The modification of $\cos(Z)$

Effective hourly solar zenith angle that correctly relates hourly direct horizontal irradiance and hourly direct normal irradiance has been studied (Blanc and Wald, 2016), and the CERES hourly solar zenith angle, *Z*, which is based on the relation between the hourly DirHI and DNI, or solar constant, at TOA, is one of the six methods studied. According to the study, the best result is based on a surface clear-sky model that computes clear-sky hourly DirHI and DNI.

Here, however, we will only modify the cos(Z) by adding a linear component for large Z values to prevent cos(Z) from getting too small. When $Z > 75^{\circ}$, the value cos(Z) approaches 0 infinitesimally as the DirHI also approaches 0 and, and the error becomes a more and more significant part of the DirHI value. Consequently, the derived DNI, or DirHI/cos(Z) becomes haphazardly, or unphysically, large. The following correction of cos(Z) for $Z > 75^{\circ}$ is proposed.

Let μ stand for cos(Z), and μ_{eff} for effective cos(SZA). If $Z \le 75^{\circ}$, then $\mu_{eff} = \mu$; if $Z > 75^{\circ}$, then $\mu_{eff} = \mu + \mu_A$, where $\mu_A = -\frac{k}{\mu_{75d}}\mu + k$, $\mu_{75d} = \cos 75^{\circ}$, and k is an adjustable parameter, and when k = 0.045, the biases are minimized for $Z > 75^{\circ}$. In fact, the biases in all twenty 0.05-sized bins become one digit.

The corrected DHI, DirHI and derived DNI therefrom as compared to BSRN are shown in Figs. 4-6. The corrected GHI is not shown here due to limited space; it looks similar to Fig. 1 except with even smaller biases and other statistics, and the biases in all bins of cos(Z) are close to zero. Note that the BSRN data have been quality-checked, and Zhang et al. (2013) details the quality-check procedure.

Although the lower panels in Figs. 4-6 show that the site-by-site biases scatter around 0 over wide ranges, 43 sites of 70 in Fig. 6f are actually within $\pm 10\%$. The larger biases at other sites do not necessarily mean bad data. Schwarz et al. (2018) studied how the BSRN point observations represent their larger surroundings, and they found that 26 sites out of 47 sites in the range from 50°S to 55°N are representative of their larger surroundings according to different metrics. Therefore, caution is advised when interpreting the differences between satellite-based and ground-based data.



Fig. 4. Comparison of the corrected CERES SYN1deg (Ed4.1) hourly DHI with the BSRN data from 2000-03 to 2020-07. a) The scatter density of the hourly GHI. The statistics shown are categorized as "Global" that includes all data points, "60° Poleward" and "60° Equatorward"; ρ stands for correlation coefficient, ρ standard deviation, μ BSRN the BSRN mean, and N the total number of data points. b) Histogram of the SYN1deg (Ed4.1)-BSRN hourly GHI differences. c) and d) The biases in 20 bins of cos(Z) on absolute and relative scale, respectively. e) and f) The bias, σ and p on a site-by-site basis.



Fig. 5. Same as Fig. 4 except for DirHI, which is the difference between GHI and DHI, or GHI-DHI.



Fig. 6. Same as Fig. 5 except for corrected DNI, or DirHI/cos(Z).

5 Summary and Conclusions

The POWER WSS project needs GHI, DHI and, in particular, DNI. The CERES SYN1deg (Ed4.1) has hourly GHI and DHI, but not DNI, and instead, it has DirHI. However, it has been found that the DHI is positively biased against BSRN and, the DirHI is negatively biased against BSRN, and the biases become more and more pronounced as $\cos(Z)$ increases. Consequently, the derived DNI, or DirHI/ $\cos(Z)$, is also negatively biased. In addition, the $\cos(Z)$ value approaches 0 infinitesimally toward sunset, and the derived DNI becomes haphazardly and unphysically large. Therefore, we performed a bias-based correction of the GHI and DHI, and use their difference, GHI-DHI as corrected DirHI, and the $\cos(Z)$ is modified by adding a linear component to $\cos(Z)$ when $Z > 75^{\circ}$. The corrected DNI shows an overall minimal bias, and in all the 20 bins of $\cos(Z)$, the biases are all 1-digit on both the absolute and relative scales. More importantly, the overall standard deviation of the differences, or uncertainty, is significantly smaller than that of the DNI computed using the DirIndex model. To access the POWER solar data, visit <u>https://power.larc.nasa.gov</u>, select DATA ACCESS, then click POWER DATA ACCESSS VIEWER, click Access Data, select Renewable Energy, and the follow steps to select the data parameters and temporal averaging for a particular location. A complete Application Programing Interface is also provided as well as limited image services. Please see the main homepage for details.

6 Acknowledgments

The Prediction of Worldwide Energy Resource (POWER) Project is funded through the NASA Science Mission Directorate Earth Science Division including Earth Applied Sciences (Mr. L. Friedl), Advanced Information Technology (Dr. J. Lemoigne-Stewart) and Research and Analysis programs (Dr. J. Kaye, Dr. L. Tsaoussi, Dr. H. Maring).

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Towards more precise estimates of land-use requirements for solar photovoltaic power plants

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Abstract

There is a lack of PV module rating agnostic research in solar PV power plant land use requirements. Existing literature focuses on peak capacity (watts) or energy (watt-hours) per unit area, which limits the validity of the results as the age from publication increases due to the rapid (and ongoing) increase in PV module performance.

The aim of this paper is to derive a relationship for the Ground Coverage Ratio (GCR, ratio of total solar PV module area to total land area) of a single-axis solar PV power plant to be used as an accurate, yet simple, model for land use prediction.

In this paper, a toolkit was created using the Python programming language to create a solar PV power plant layout, given a land parcel polygon selected from actual (scaled) cadastral land boundaries in Victoria, Australia.

Approximately 200,000 solar PV power plant layouts were simulated across 8 permutations of design criteria. Whilst no clear correlation was found between any land parcel properties and the GCR, all permutations indicated a relatively uniform GCR which was highly correlated with the natural logarithm of the row spacing.

By deriving the land use requirements of single-axis solar PV power plants based on design principles such as row spacing, azimuth tolerance and perimeter setback – but not module capacity – the results of this paper remain relevant into the future even with increasing solar PV module capacity.

Keywords: Solar PV power plant, land-use, solar farm, spacing, area

1. Introduction

Recent years have seen the rapid development of large-scale solar photovoltaic (PV) power plants throughout the world. Given the focus on reducing the effects of global warming, analysis to deduce the required area to supply a state, province or country with large-scale solar PV power plants has become both more prevalent in the literature and of greater importance for industry and government throughout the globe.

2. Literature Review & Scope

A high-level review of the literature was completed to identify existing spatial requirements for large-scale solar PV power plants, which are summarized below. Note the units have been converted by the author to a common unit (W/m^2) where feasible to allow direct comparison.

- Denholm and Margolis (2008) calculated 48.0 Wdc/m² for a single-axis tracking solar PV power plants as part of a wider analysis.
- Hernandez et al (2013) analysed 57 existing and planned solar PV power plants and deduced a range of 29.7 W/m² to 35.0 W/m². 13 peer review studies were also reviewed, however significant variance in the data was observed.
- Ong et al (2013) calculated the capacity-weighted average of 55 existing single-axis tracking solar PV power plants in the USA as 28.4 W/m².
- Horner and Clark (2013) condensed a wide range of studies on land use requirements and concluded a landuse estimate range of 5-55 m²y/MWh for various types of solar power plants, including solar PV and CSP.
- Wachs and Engel (2021) assessed 12 papers, identifying a range of land use requirements, but noted 'Land use efficiency for solar [PV] has increased dramatically due to technological improvements, and newer assessments are needed that take into account improved efficiency'

This point by Wachs and Engel is critical. All studies considered above derive land use efficiency based on peak capacity (W) or total power output (Wh), overlooking the critical factor of Ground Coverage Ratio (GCR) which is the ratio of total solar PV module capacity to total land area.

By concluding land requirements in terms of capacity or power, the results presented become less accurate as their age from publication increases, due to the rapid (and ongoing) increase in module performance and efficiency (Figure 1). A solar PV power plant installed in the future will almost certainly use higher efficiency panels than those installed previously, which in turn leads to an increase in power plant power output for the same area, resulting in lower land required for the same output capacity.



Based on this common limitation, this paper presents a forward-looking study to deduce the land-use requirements of large-scale solar photovoltaic (PV) power plants from facility design principles, with the aim to derive a relationship for GCR which can be used into the future as solar module capacity continues to grow.

The remainder of this paper is structured as follows. Sections 3 and 4 describes the core design assumptions, based on Australian large-scale solar PV industry best practice design, which are used as inputs in Section 5 to a custom developed Python software package which generates a solar PV power plant layout. Section 6 discusses the results from this software package using land parcel data and deduces relationships to estimate power plant capacity for a given land size. Conclusions and future work are discussed in Section 7.

3. Assumptions – Solar Design

To focus the scope of this investigation, single-axis tracking solar PV systems similar to the below in Figure 2 have only been considered. This technology is used in multiple developed and planned large-scale solar PV power plants within Australia (ARENA, 2018).



Fig. 2: Single-axis solar PV power plant in Australia

Unfortunately, there are not (to the authors knowledge) any Australian, nor international, industry design practice guidelines from which to reference the design criteria for a single-axis tracking solar PV power plant. Instead, the author provides the following as assumptions for this analysis based on project design & development experience.

Solar power plants use solar modules (panels) with typical dimensions of ~1000 mm wide by ~2000 mm tall, typically installed in a portrait arrangement as per Figure 2 above. For this investigation we have assumed module dimensions of 1000 mm by 2000 mm.

Single-axis solar PV power plants feature a series of modules on a common structure. This structure is typically aligned towards the equator (though can be orientated away from true north/south within a small tolerance without a significant impact to power plant yield) and rotates east-west to track the sun. The number of modules per row structure varies but is commonly an integer multiple of the string length chosen by the designer. Row lengths of one string, two strings and three strings are the most common. Many modern Australian solar PV power plants use 1500 V_{DC} strings, meaning for a 'typical' solar module string lengths are usually in the range of 25 to 28 modules, with higher preferred due to lower copper losses in the DC cabling. For this investigation we have

assumed 28 modules per string giving total row lengths of 32 m (1 string), 60 m (2 strings) and 88 m (3 strings) with an allowance of 4.0 m for supporting equipment such as slew motor, pier mounts and spacers.

The east-west spacing between row structures is typically selected by the power plant designer, but in the Australian market typically falls between 4.0 and 7.0 m 'post-post' (horizontal distance from middle of one row structure to the middle of the second). Lower spacing between row structures can cause interrow shading, reducing the specific yield (kWh / kWp / year) of the power plant but also increasing the peak output (kWac) of the power plant – effectively each module is less efficient but more fit modules overall. Maintenance access and common fire-fighting spacing requirements often lead to higher interrow spacing within Australia solar PV power plants. For this investigation we have considered interrow spacing between 4.0 to 7.0 m.

In the author's experience, there are two common row layout design themes for solar PV power plants, 'block' alignment and 'boundary edge' alignment. Block alignment aims to create consistent blocks of rows (and an associated inverter station) which can be duplicated and is commonly used for extremely large solar PV power plants with ample available land area. Boundary edge alignment aims to use all available area by aligning the rows to the edge of the land area, typically creating irregular layouts. As boundary edge alignment typically gives a higher capacity than block alignment (as it aims to use all available land) it has been used in this investigation.

A setback from the property edge is common for large-scale solar PV power plants in Australia based on local fire-fighting requirements. A clear space of 10.0 m from the edge to the nearest module is common and thus for this investigation we have considered property edge setbacks from 0.0 to 10.0 m.

Access roadways are important for maintenance access for all large-scale solar PV power plants. Design criteria for roadways differ based on the facility owner's requirements and local fire-fighting access requirements. A perimeter roadway within the fire-fighting exclusion zone is very common and has been included in this investigation whenever the perimeter setback is greater than 0 m. For this investigation, we assume internal horizontal roadways are provided at the end of every two rows of maximum length, meaning roadways are spaced within the facility approximately 200 m apart. We have also assumed that this roadway is contained within an 8.0 m clear section between the end of rows, with this space to be used for the roadway itself, inverter stations and cable trenches. In the author's experience, this represents the minimum quantity of access roads required to allow efficient maintenance of the power plant.



Fig. 3: Example solar PV power plant layout showing a single internal road (8.0 m clearway) and a perimeter road

Solar PV power plants typically require connection assets, such as collector switchgear and main transformer(s) to step-up the voltage to transmission level or otherwise. The location of these assets is commonly driven by the location of the nearest network asset (such as an overhead line or existing substation) rather than what the optimal location is for the asset based on the available land. For example, if the nearest connection point into the local

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network is an overhead line to the north-east of the site, the north-east corner of the available land is a good candidate for the location of these connection assets, as is a small piece of land just outside of the power plant land. Based on this restriction (unclear where, if at all, this asset should be located within the site) we have not included any spacing for connection assets in this investigation. This means this investigation may slightly underestimate the land required for a given solar PV power plant.

Parameter	Varied during analysis?	Value	Notes
Module dimensions	No, fixed value	1000 mm x 2000 mm	
String length	No, fixed value	28 modules	To suit to 1500 V_{DC} inverters
Row type	No, fixed value	Single-axis single module (portrait) tracking system	Similar to Figure 2 above
Azimuth Tolerance	Yes	±5°, ±10°, ±15°	Allowable tolerance away from true north
Row lengths (3, 2 & 1 string)	No, fixed value	88.0, 60.0, 32.0 m	Assuming 4.0 m for row structure, motor, pier mounts and spacers
Row spacing	Yes	4.0, 5.0, 6.0, 7.0 m	Post-post spacing
Row alignment	No, fixed value	Boundary edge alignment	
Property boundary setback	Yes	0.0, 5.0, 10.0 m	
Perimeter access roadways	No, fixed value	Only if setback > 0.0m	
Internal access roadways	No, fixed value	8.0 m clearway east-west every ~200 m vertically	No vertical roadways
Spacing for connection assets in power plant	No, fixed value	Not included	

Tab. 1: Assumed solar PV power plant design parameters for this investigation

4. Assumptions – Land Area

In this section we discuss the assumptions on the land parcels used for this analysis.

For this investigation we have considered solar PV power plant facility layouts in only two dimensions, as full three-dimensional layout generation is complex. As solar PV facilities in Australia are predominantly developed on flat land, the variation between 2D and 3D analysis would likely be small and thus has been ignored in this study.

We have also assumed that each land parcel has no overlay restrictions (such as trees, waterways, locations of cultural or ecological significance etc) as attempting to parametrize this requirement without introducing substantial bias in the results is difficult.

To increase the validity of the results, the polygons representing the land area for the solar PV power plants were selected from the 'Vicmap Property' (2021) data set, which represents the cadastral boundaries of all land titles in the state of Victoria, Australia. Polygons representing the boundaries were extracted from the shapefile in the Vicmap Property database and scaled to a unit area for analysis prior to inclusion in the analysis dataset. The process is described below (summarized in Table 2) and was completed using the Python toolkit developed for this application, which is further discussed in Section 5.

Firstly, any polygons representing the available land area with self-intersections (Table 2, ref 1) or similar data

quality errors (such as two areas connected by a very thin segment) were not added to the data set.

A land parcel which is skinny in one axis, yet wide in another, is typically not economically viable as a solar PV power plant due to the long DC and AC cables required. If extremely skinny in one axis, limitations on maximum row length can also be imposed which further prohibits economic viability (requires significantly more structures to install). As per Table 2 ref 2 below, these land parcels are excluded by a test which calculates the ratio of the length L_{MBB} to the width W_{MBB} of the minimum rotated rectangle (rotated bounding box) of the land parcel. Note the length L_{MBB} is defined as the longest side of the minimum rotated rectangle. If this value is greater than 3.0 the land parcel is not added to the data set.

Similarly, if the land is skinny in one axis and contains one or more segments (for example, an L shaped piece of land) it may not be economically viable to develop either. As per Table 2 ref 3 below, these land parcels are excluded by calculating the ratio of the area of the land parcel and the area of the minimum rotated rectangle. If the value is less than 0.1 the land parcel is not added to the data set.

Finally, prior to adding the land parcel to the analysis dataset, the raw land parcel is compared to all other land parcels already in the analysis dataset. If each vertex of the land parcel polygon is within 0.05 units (for the scaled polygon) of a corresponding vertex on a land parcel in the data set, it is not included. This is to avoid introducing bias in the results by adding multiple similar land parcels. Refer to Table 2 ref 4 below.

Ref	Name	Calculation	Skipped if	Example of polygon which is <u>not</u> added to dataset
1	Self-intersection or Fragmented	N/A	Detected	
2	Land aspect ratio	L _{MRR} W _{MRR}	> 3.0	
3	Minimum rotated rectangle area ratio	$rac{A_{Land}}{A_{MRR}}$	< 0.1	
4	Polygon similarity	N minimum distances	< 5.0 %	

Tab. 2: Assumed solar PV power plant design parameters for this investigation

Using the above process, a subset of 500 polygons was selected. To further reduce land parcel bias, the polygon area and rotation was linearly scaled throughout the entire dataset. Final land parcel areas ranged from $30,000 \text{ m}^2$ to $550,000 \text{ m}^2$, which is approximately equivalent to 1.0 to 20.0 MWac assuming the upper range of 35 W/m2 calculated by Hernandez et al (2013). This area band was specifically selected to strike a balance between

reasonable simulation time whilst maintaining feasibility of extrapolating the results to much larger solar PV power plants.

To visually confirm if there was any clear polygon bias in the data set, the polygons were scaled to area of one and plotted with aligned centroids and high transparency using Python. Bias to a particular shape or orientation of land would appear as a bold line or series of lines, which were not observed as per Figure 4 below.



Data Set #1 (N=500)

Fig. 4: Centroid aligned unit area scaled polygons within data set plotted with high transparency. No duplicates of the same shape on the same rotational axis can be seen (would appear as bold, distinct lines). Concentration of polygon boundaries into an annulus is likely caused by the unit scaling of the polygon boundaries.

5. Solar PV Power Plant Layout in Python & Method

In this section we discuss the method used of deriving the solar PV power plant layout given the design criteria discussed in Section 3 and the land parcels selected in Section 4.

A toolkit was developed for this project in Python and is publicly available (see Section 7). The toolkit uses multiple Python libraries such as *shapely* (polygon & planar feature analysis), *matplotlib* and *seaborn* (plotting), *numpy* (numerical analysis), *statsmodels* (statistics & curve fitting) and *pyshp* (shapefile library).

The base toolkit creates a solar PV power plant layout based on design criteria like that discussed in Section 3. Design optimization can be achieved by iterating over design values (such as azimuth, row spacing etc) and rerunning the algorithm. For this investigation, the design optimization target was to achieve the highest number of modules on the site.

Up to 50 different design permutations were calculated for each of the 500 land parcels. This process was repeated 8 times to investigate the impact of row spacing, allowable azimuth tolerance and perimeter setback, giving an approximate total of 200,000 simulations being completed.

Data describing the resulting solar PV power plant was recorded for the best result (highest number of modules) from the 50 design permutations.

A total of 8 separate iterations (sequences of 500 land parcel studies) were completed and summarised in Table 3 below. The results of these iterations are discussed in the next section.

Iteration #	Inter-row Spacing	Perimeter Offset	Azimuth Tolerance
1	6.0 m	10.0 m	±10°
2	7.0 m	10.0 m	±10°

Tab. 3: Summary of the 8 iterations completed in this investigation

Iteration #	Inter-row Spacing	Perimeter Offset	Azimuth Tolerance
3	5.0 m	10.0 m	±10°
4	4.0 m	10.0 m	±10°
5	6.0 m	5.0 m	±10°
6	6.0 m	0.0 m	±10°
7	6.0 m	10.0 m	±5°
8	6.0 m	10.0 m	±15°

An example of a 'best' layout (the highest number of modules from the 50 layouts generated for this land parcel for a given iteration) as generated by the toolkit is shown below.



ID #295 Best Result

Fig. 5: Example 'best' layout (highest number of modules) generated by the brute-force optimisation algorithm for this land parcel polygon.

6. Results & Discussion

6.1 Definition of GCR

In this section we discuss the results of the Python simulations completed. As per Section 2, all results will be discussed in terms of Ground Coverage Ratio (GCR) which is the ratio of total solar module area to total available land area, as shown below.

$$GCR = \frac{N_{module}L_{module}W_{module}}{A_{Land}} \tag{1}$$

Where:

- N_{module} is the number of modules on the entire site
- L_{module} and W_{module} are the length and width of the module respectively (m)
- A_{Land} is the area of the land parcel (m^2)

Note occasionally solar PV power plant land use efficiency is described in terms of packing factor (pf) which is the reciprocal of GCR.

6.2 Analysis of Results

To begin our analysis, we will investigate single variable correlations between properties of the land parcel polygon and the calculated GCR for iteration #1 as per Table 3.

Tab. 4: Single variable linear correlations for iteration #1 as per Table 3. Refer to Table 2 for definitions of the independent variables used.

Independent Variable	Dependent Variable	Linear <i>R</i> ² Correlation
Land area		< 0.1
Land aspect ratio	GCR	< 0.1
Minimum rotated rectangle area ratio		< 0.1

As shown above, all parameters tested show no linear correlation to GCR, indicating that they are not a useful predictor of GCR for any given land parcel. This was expected due to the significant variation in land parcel polygons which could give an identical area, aspect ratio or minimum rotated rectangle area ratio. Results of a similar magnitude were identified for the other iterations completed.

Several permutations of multivariate linear and non-linear correlations were considered for the independent variables above, but all showed weak correlation ($R^2 < 0.2$) and occasionally very large condition numbers, indicating potential multicollinearity in the results (which is likely, given polygon area and minimum rotated rectangle area ratio are somewhat related).

Analysis was then completed to determine the variability of the GCR within the results of a single iteration (500 land parcels). A box plot of the data (Figure 6, Left) of the GCR shows a very narrow 95% confidence band for the median in addition to a relatively narrow interquartile range. This implies that, although it appears hard to predict based on land parcel properties, the estimated GCR of any given land parcel appears relatively constant.

The analysis was then expanded to include variable post-post row spacing (iterations #1 through #4). As expected, the median GCR (Figure 6, Right) steadily increased with reducing interrow spacing. The interquartile range was relatively uniform, but upon visual inspection appears to be slightly positively correlated to the interrow spacing.



Fig. 6: (Left) Boxplot of results of iteration #1, showing relatively narrow 95% confidence interval for median and relatively narrow interquartile range.

(Right) Boxplot of results of iterations #1 through #4, showing non-linear increase in GCR for linear decrease in row spacing. Note vertical axis is reversed.

Iterations #1, #5 and #6 were then considered to investigate the effect of variable land parcel perimeter offset (Figure 7). No clear relationship was identified, however a small difference in the minimum and maximum values
of the boxplots is likely attributed to the discrete nature of solar PV row structures – a small increase in available land may not allow additional modules, but the increase in available land corresponds to a decrease in GCR. This hypothesis is reinforced by the alignment of all median values for this study.



Fig. 7: Boxplot of results of iteration #1, #5 and #6 indicating no material variability or relationship between GCR and perimeter offset for a solar PV power plant.

Iterations #1, #7 and #8 were considered together to investigate the effect of allowable azimuth tolerance. To prevent giving an advantage to any one iteration and to allow direct comparison, the number of optimisation steps the brute-force algorithm could complete was identical between iterations #1, #7 and #8. An interesting relationship can be seen in Figure 8 below – a higher azimuth tolerance window (up to $\pm 15^{\circ}$ away from true north/south) resulted in lower variance to the GCR, but only marginally achieved a higher median than the other, lower, azimuth tolerances. This is likely as the layout algorithm can better align the module rows to the perimeter of the land parcel with higher azimuth tolerance.

Importantly, we note as azimuth angle increases away from true north (for the Southern Hemisphere) the specific yield of the solar PV power plant decreases due to the modules being orientated sub-optimally. This implies that a higher azimuth tolerance angle may not be preferred in a final solar PV power plant design compared to one with lower azimuth tolerance.



Fig. 8: Boxplot of results of iteration #1, #7 and #8 indicating the variability of GCR decreases with increasing azimuth tolerance.

To summarise the analysis completed:

- There was no reliable linear, multivariate linear or non-linear relationship identified between any of the land parcel parameters (area, aspect ratio or minimum rotated rectangle area ratio) and GCR.
- A strong non-linear relationship was identified between post-post row spacing and GCR.
- No relationship was identified between perimeter setback and GCR.
- Although the variance of GCR appeared correlated with the azimuth tolerance, the median GCR did not appear to be strongly correlated to azimuth tolerance.

6.3 Derivation of Models

Based on the above analysis, two results can be derived. Given the design and land parcel assumptions in Section 3 and 4 above and all iterations completed, Python was used to calculate the mean GCR, a 95% confidence interval for this mean and the standard deviation for the aggregate of all iterations (#1 through #8) completed.

If no prior knowledge is known about the land use parcel or the solar PV power plant desired (within the bounds of the assumptions in Section 3 and 4 above) the following mean GCR can be used.

Tab. 5: Derived mean GCR, confidence interval and standard deviation from the aggregate result of all iterations completed in this study.

GCR Assuming no prior design/land knowledge			
Mean	95% confidence interval for mean	Standard deviation	
32.39%	32.08 - 32.70%	7.04	

However, if the row spacing R is known (or selected) the accuracy of the estimation can be improved beyond a simple mean and standard deviation.

Based on Figure 6 (right) above, we can see a clear non-linear relationship between row spacing and the median GCR. Using least squares regression in Python, the natural logarithm of the row length independent variable was used to deduce a very strong relationship (Figure 9). Iterations #1 through #4 were only used in the calculation of this line of best fit to prevent over-weight of the row length = 6.0 m condition (iterations #5 through #8).



Fig. 9: Least squares fit between GCR & log(row spacing). Note axis coordinates are arranged to align with visual representation of box plots, independent variable is on vertical axis.

Tab. 6: Derived relationship between GCR and row spacing R from iterations #1 through #4.

GCR Assuming no prior land knowledge Assuming row spacing R (m) is known		
Equation R ² Correlation		
$GCR = 87.45 - 32.71 \cdot \log R$ $4.0 \le R \le 7.0$	0.837	

6.4 Example Calculation

Converting GCR to MWac can be completed as follows, based on the solar PV power plant designer's selection of:

- PV module, which has a STC capacity of M (W), length L_{module} and width W_{module} (m)
- Inverter DC/AC oversizing ratio r
- Row spacing R (for this example we have assumed this is not selected at this stage, if it was known the *GCR* below would be replaced with the equation in Table 6 above)

$$M_{Plant} = \frac{M}{r} \cdot \frac{GCR \cdot A_{Land}}{L_{module} W_{module}}$$
(2)

For example, based on a typical solar PV module capacity used in large-scale solar PV power plants as of time of writing and the author's project experience:

- $M \approx 600 \text{ W}$
- $L_{module} W_{module} \approx 2 \text{ m}^2$
- DC/AC oversizing ratio $r \approx 1.25$
- GCR = 32.39% (the mean from Table 5 above)

$$M_{Plant} = \frac{600}{1.25} \cdot \frac{0.3239 \cdot A_{Land}}{2} = 77.74 \, \text{W/m}^2 \tag{3}$$

However, the author cautions the direct application of the above result. Solar PV module capacity is likely to continue to improve into the future meaning the selection of $M \approx 600$ W may not be appropriate in the future.

We also observe that repeating the above calculation with M = 295 W (based on the 2010 data point in Figure 1) $M_{plant} \approx 38$ W/m² which shows good alignment with the upper band of the values identified in the literature in Section 2.

7. Future Work & Conclusion

In this paper we have explored single-axis solar PV power plant land use requirements and derived empirical results for both the 'no prior knowledge' case and the 'row spacing knowledge' case.

Future work to expand the body of knowledge could consider the use of dual-portrait single-axis tracking systems as well as fixed-tilt systems. Variable row lengths, though uncommon, could also be investigated to improve the accuracy of the simplified logarithmic model.

The Python library used to generate the results in this section is publicly available and can be found online at the following GitHub link <u>https://github.com/damienvermeer/sfl</u>.

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L-02. Solar Resource Models and Data

One-Minute Assessment of Photosynthetically Active Radiation (PAR) Models in Uruguay

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Abstract

Photosynthetically Active Radiation (PAR) is the spectral portion of global solar radiation that is primarily relevant to plants' growth processes (between 400 and 700 nm). The PAR fraction (f_p) is the ratio at horizontal surface between the photon's flux per square meter (Q_p) and the global solar irradiance (G_h). In this work, the first assessment in Uruguay of PAR fraction empirical models is presented using 4 years of 1-minute measured data for one site representative of the Pampa Húmeda region. The chosen models have been developed for the 1-hour time scale and use the clearness index and/or the solar altitude as predictive variables. Original and locally adjusted versions of these models are evaluated and compared with the utilization of a constant PAR fraction value (as frequently done in agronomical practice). It is found that polynomial k_t models with original coefficients have acceptable performance, but they cannot be used with locally adjusted coefficients at the 1-minute timescale.

Keywords: PAR radiation, PAR fraction, empirical models, GHI.

1. Introduction

Photosynthetically Active Radiation (PAR) is the portion of solar radiation in the spectral interval 400-700 nm. Part of this radiation is used by plants for photosynthesis and its characterization in a given region is highly relevant for modeling plant growth rates and for proper planning of agricultural production. PAR radiation is measured by specialized sensors as the photon flux (in the 400-700 nm interval) per unit area and expressed as μ mol/m²s. On a horizontal surface, this magnitude is denoted by Q_p and it is highly correlated with the global horizontal irradiance, G_h or GHI. If a specialized sensor is not available, Q_p can be indirectly estimated from pyranometer measurements by using an infrared filter which effectively blocks solar irradiance above 700 nm. One of the problems associated with this approach is that, unless an independent UV measurement is available, all UV irradiance below 400 nm will be counted as PAR radiation. For locations for which no PAR measurements are available, Q_p can be estimated from GHI using either a constant PAR fraction or an empirical model, being the latter a lower uncertainty option.

The PAR fraction, which is the quantity of interest in this work, is the ratio $f_p = Q_p / G_h$ expressed in µmol/J. Several previous studies (see for example Tsubo and Walker, 2007) have reported mean PAR fractions between 1.96 and 2.23 µmol/J. Most of these works are based on hourly data from sites in the northern hemisphere. Some authors in the literature work with PAR irradiance (G_p), i.e. the global horizontal irradiance between 400 and 700 nm expressed in W/m², either for convenience or for practical reasons (such as indirect measurements). However, Q_p and PAR irradiance are not strictly proportional, since their

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ratio depends on the detailed surface solar spectrum at the time and conditions of the measurement. Frequently, this fact is ignored and an approximate conversion constant is calculated from the average incident extraterrestrial solar spectrum. This simple calculation, using the standard ASTM E490 solar spectrum (https://www.astm.org/Standards/E490.htm) normalized to a total solar irradiance of 1361 W/m² (Kopp and Lean, 2011) leads to a conversion constant $\kappa = Q_p / G_p = 4,566 \ \mu mol/J$. This value has been used in this work to convert PAR irradiance to photon flux units when referring to published works, with the exception of the work of Tiba and Leal (2007), since these authors explicitly convert the measured photon flux to PAR irradiance using a constant of 4.60 $\mu mol/J$.

The focus of this work is the Pampa Húmeda region in southeastern South America, which is climatically and geographically homogeneous and includes parts of Argentina, southern Brazil and the territory of Uruguay. In this region, the percentage of surface area dedicated to agriculture and crop production is among the highest in the world (http://www.fao.org/). For this area, an average PAR fraction of 2.10 µmol/J has been reported in (Grossi Gallegos, 2004) using 26 days of hourly data. Worldwide, most previous work on PAR fraction modelling has been done using hourly or daily data.

As mentioned, the PAR fraction f_p depends on the spectral distribution of solar radiation at ground level, which in turn depends on the state of the atmosphere (precipitable water and aerosol type and content are the main atmospheric factors identified in Alados et al, 1996) and on the air mass or, equivalently, on the Sun's zenith angle (z). Thus, the most relevant variables for PAR fraction modeling are the clearness index ($k_t = G_h / G_0 \cos(z)$, where $G_0 = S \times F_n$ is the solar irradiance incident at the top of the atmosphere, TOA, being S = 1361 W/m² the mean total solar irradiance (TSI) and F_n the orbital correction factor) and the solar zenith angle, which can be calculated for each site and time (Iqbal, 1983).

In this work, four pre-existing empirical models for PAR fraction estimation (which use these two variables as descriptors) are evaluated using a quality-controlled 4-year dataset with 1-minute time resolution from a site representative of the Pampa Húmeda region. Sets of good quality simultaneous PAR and GHI measurements are scarce in this region. However, the target region is highly homogeneous with respect to geography and climate. In particular, within the Uruguayan territory the spatial variability of the long-term mean annual solar irradiance (GHI) is below ± 5 % of the mean value of 16.9 MJ/m² (Alonso-Suárez et al. 2014). Both the original and locally adapted versions of these models are evaluated. The simple approach of considering fp = constant, commonly used by agronomical practitioners, is used as a performance baseline in this work. These models have been chosen for having been developed in a geographical proximity to the region of interest, with the exception of the model by Alados et al. (1996) which was developed using high quality data from Almeria, Spain. A summary of the considered models is shown in Table 1, including their citation, and the location and time-span of the measurements used for their original local training. This is the first work evaluating PAR fraction models in Uruguay and one of the few worldwide on the subject working at the 1-minute time scale

This work is organized as follows. Section 2 describes the data being used and its quality assessment, and the models and methodology for their local adjustment and assessment. Section 3 presents the uncertainty evaluation of both original and local adjusted models, and provides recommendations for their utilization in the Pampa Húmeda region. Finally, Section 4 summarizes the main conclusions of this work.

Table 1: Details for the PAR fraction models evaluated in this work. The "type" column refers to whether the PAR photon flux was measured (direct) or estimated from filtered global irradiance measurements (indirect). GG is included as a previous report of the average PAR fraction (constant) for the area of interest. All models considered have been originally developed for the hourly time scale.

Label	Reference	time of measurements	length	type	Location
AL	Alados et al., 1996	1990-1992	2.5 years	direct	Almeria, Spain
TL	Tiba and Leal, 2004	2003-2004	1 year	direct	Recife, Brazil
ES	Escobedo et al., 2006	2001-2005	4 years	indirect	São Paulo, Brazil
TW	Tsubo and Walker, 2007	2000	86 days	direct	South Africa
GG	Grossi et al., 2004	2003	26 days	indirect	San Miguel, Argentina

2. Data and methodology

The measurements used in this work include global horizontal irradiance (G_h or GHI), diffuse horizontal irradiance (G_{dh} or DHI) and Q_p , the PAR photon flux. They were registered between 2016 and 2019 at 1-minute intervals (average of four samples) at the experimental facility of the Solar Energy Laboratory (LES, http://les.edu.uy/) in Salto, Uruguay (latitude = -31.28°, longitude = -57.92° and altitude = 46 m above mean sea level).

The region's climate is classified in the updated Köppen-Geiger classification (Peel et al., 2007) as Cfa (temperate, without dry season and hot summers) with the exception of a small coastal portion dominated by the influence of the Atlantic Ocean, that is classified as Cfb (temperate, without dry season and warm summers). The data used in this work is considered as representative of this broader region.

The G_h and G_{dh} measurements were made with Kipp & Zonen CMP10 pyranometers (spectrally-flat Class A according to the ISO 9060:2018 standard). These pyranometers were mounted on a SOLYS2 Kipp & Zonen solar tracker equipped with CVF4 ventilation and heating units to prevent the accumulation of dust and water droplets on its domes. The SOLYS2 tracker was equipped with a standard shading ball assembly in order to measure G_{dh} , which in this work is only used to strengthen the quality control tests. Both pyranometers have been calibrated every two years against a Kipp & Zonen CMP22 (used as a Secondary Standard pyranometer, Abal et al., 2018) which is kept traceable to the World Radiometric Reference in Davos, Switzerland. The Q_p measurements were made using a Kipp & Zonen PQS1 quantum sensor with factory calibration at the start of the data series.

2.1 Data quality

Quality control of the raw data is of the highest importance when evaluating radiation models. Our quality control procedures are applied in two steps. First, a careful inspection of the dataset is done to remove obvious anomalies (shadows, extreme values, astronomical events such as eclipses, etc.) and diurnal records are selected using the condition cos(z) > 0. As a result of this first process, there is a base set of 832108 positive daytime records with the three measurements used here (G_h, G_{dh}, Q_p) .

The second step consists of a set of eight quality filters (F1 to F8 in Table 2) which are applied independently to the dataset. These include the relevant BSRN quality procedures (Long and Shi, 2006) for G_h and G_{dh} and also some restrictions on valid Q_p values, as explained below.

F1 selects records with solar altitude > 7° in order to avoid the large uncertainties typical of low-sun conditions. F2 and F3 apply BSRN upper limits with local parameters adequate for the measuring site to GHI and DHI, respectively. F4 filters out points with low clearness index k_t (associated with cloudy conditions) and low diffuse fraction f_d (clear-sky conditions). F5 applies BSRN upper limits to f_d with a tolerance of 5 or 10 % depending on solar altitude. F6 applies an upper limit to the modified clearness index (Perez et al, 1990). F7 applies minimum and maximum limits to the PAR fraction f_p in µmol/J, obtained after inspection of the data.

Filter	Description	Condition	parameters	% discarded
F1	min solar altitude	cos(z) > cz min	<i>cz</i> min = 0.1219	0.7
F2	upper limit in <i>G_h</i>	$G_h < Go.fcos^a(z) + c$	f = 1.15, a = 1.25, c = 20	0.1
F3	upper limit in <i>G_{dh}</i>	$G_{dh} < Go.fcos^a(z) + c$	f = 1.15, a = 1.25, c = 20	0.0
F4	lower limit for f_d	if $k_t < k_t max$, $f_d > f_d min$	$k_t \max = 0.20,$ $f_d \min = 0.90$	2.7
F5	upper limit for f_d	for $z < 75^{\circ}$, $f_d < f_d max 1$ for $z \ge 75^{\circ}$, $f_d < f_d max 2$	$f_d \max l = 1.05$ $f_d \max 2 = 1.10$	0.8
F6	limits on k_{tp}	$0 < k_{tp} < k_{tp} max$	$k_{tp} max = 1.35$	0.0
F7	limits on f_p	$f_p \min < f_p < f_p max$	$f_p \min = 1.7 \ \mu mol/J$ $f_p \max = 10 \ \mu mol/J$	0.4
F8	limits on Q_p	$\alpha_{min}k_t < Q_p < \alpha_{max}k_t$	$\alpha_{min} = 340 \ \mu mol/m^2 s$ $\alpha_{max} = 4000 \ \mu mol/m^2 s$	1.5
ALL	all filters	all the above conditions		4.9

Table 2: Set of quality control filters applied to the dataset and percentage discarded with respect to the base dataset of 832108 daytime records. The total solar irradiance at TOA is $S = 1361 \text{ W/m}^2$.

It has been observed (Foyo-Moreno et al., 2017) that PAR flux data Q_p can be bounded by two straight lines in a Q_p vs k_t diagram. This can be understood since the PAR photon flux is highly correlated with global horizontal irradiance GHI, as shown in Fig. 1 (a). If a linear relationship is assumed, $Q_p = a \times GHI = \alpha \times k_t$, with slope of $\alpha \approx a \times G_0 / m$, in terms of the relative air mass (Kasten and Young, 1989). The extreme values for these slopes are associated to the extreme values of air mass in the data (between 1 and 8.21), to the 3% variation in G_0 due to the orbital factor and to the natural dispersion in the (Q_p, G_h) diagram. The estimated value of a, obtained by simple regression through the origin, is $a = 2.1 \pm$ 0.2 µmol/J (similar to the average PAR fraction). Taking into account these variations, extreme values of α can be estimated as $\alpha_{min} \approx 340 \ \mu mol/m^2 s$ and $\alpha_{max} \approx 2900 \ \mu mol/m^2 s$. As shown in Fig. 1 (b), the lower limit follows this slope quite well. The calculated upper limit (associated to mostly clear-sky samples) shows to over-filter portions of the data cloud, especially at low k_t values. Therefore, this slope in filter F8 has been increased in order to preserve valid data points for low k_t values. Filter F8 restricts valid Q_p data to lie between two lines through the origin with slopes of $\alpha_{min} = 340 \text{ }\mu\text{mol/m}^2\text{s}$ and $\alpha_{max} = 4000 \text{ }\mu\text{mol/m}^2\text{s}$, as shown in Fig. 1 (b). Less than 5% of the baseline records are discarded by this procedure (Table 2) resulting in 791161 records with valid (G_h , Q_p) pairs.



Figure 1: Left: Correlation between *Qp* and *Gh*; the red line results from a linear regression through the origin (intercept equal to zero). Right: Effect of filter F8 in the *Qp* and *kt* space.

The resulting PAR fraction vs clearness index scatter-plot is shown in Fig. 2. Under heavy cloud cover ($k_t < 0.20$) the PAR fraction increases sharply due to the enhanced infrared absorption and the predominance of diffuse irradiance (Iqbal, 1983). On the other hand, for $k_t > 0.20$, $f_p \approx 2 \mu \text{mol/J}$ with weak dependence on kt.



Figure 2: PAR fraction vs clearness index after all filters in Table 1 have been applied. The discarded data points are shown in red.

2.2 Models and methodology

As mentioned in the introduction, the pre-existing PAR fraction models considered in this work are those listed in Table 1. All these models are originally based on hourly aggregated data and use the clearness index k_t and the sine of the solar altitude (or, equivalently cos(z)) as independent predictor variables. In Eqs. (1) to (4) below, the parametric form for each of these models are provided,

$$\mathbf{AL} \quad f_p = a + b \ln(k_t) + c \sin\alpha_s \tag{1}$$

$$TL f_p = a (\sin \alpha_s)^b (2)$$

$$\mathbf{ES} \qquad f_p = a + bk_t + ck_t^2 + dk_t^3 \tag{3}$$

$$\mathbf{TW} \quad f_p = a + bk_t + ck_t^2 \tag{4}$$

where *a*, *b*, *c* and *d* are coefficients (in μ mol/J, except for *b* in Eq. (2) which is dimensionless) that can be adjusted to local data. The original values of these coefficients are listed in Table 3. These models are supplemented by the constant value $f_p = 2.096 \mu$ mol/J previously found from data for the Pampa Húmeda region by Grossi-Gallegos et al. (2004). Almost all models use the clearness index k_t and two of them (AL and TW) include a dependence on the relative air mass through the solar altitude angle.

The performance of these models is evaluated with their original coefficients and when the coefficients are adjusted to the local data using a standard multivariable linear regression technique. In the case of Eq. (2), the dependence on the parameter b is not linear, but it can be linearized by taking the natural logarithm of both sides.

The evaluation of the original models is done against the filtered data set. The training and evaluation of local models is done by using a standard random sampling and cross-validation method in which, at each iteration, 50% of the data is used for adjustment and the other 50% is used for testing. After 1000 iterations, the average values are used for the local parameters and for the performance indicators.

The evaluation of the models is done by calculating the residuals, $\xi = \hat{f}_p - f_p$, between the estimated PAR fraction, \hat{f}_p , and the corresponding measurement f_p . The mean bias deviation (MBD), the mean absolute deviation (MAD) and the root mean squared deviation (RMSD) metrics are used for the comparison,

$$MBD = \frac{1}{N} \sum_{i=1}^{N} \xi_i, \quad MAD = \frac{1}{N} \sum_{i=1}^{N} |\xi_i| \quad \text{and} \quad RMSD = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \xi_i^2}, \tag{5}$$

expressed in relative terms as a percentage of the measured PAR fraction average of 2.191 μ mol/J. The integer quantity N = 791161 is the number of valid 1-min data records, resulting from the quality control procedure described in Subsection 2.1

A comparison with the original performance of some of the models is not straightforward. In some cases, these metrics are not reported. In others, it is unclear if an independent data set is used for evaluation and training. For the AL and TW PAR fraction models, independent datasets for training and evaluation are used and the absolute MBD and RMSD indicators for the derived PAR irradiance (in W/m²) are reported, but the corresponding mean PAR irradiance is not given. In order to compare with these cases, the horizontal PAR irradiance is calculated as $G_p = Q_p/\kappa = f_p \times G_h/\kappa$ with $\kappa = 4.566 \mu mol/J$ and, after expressing our relative indicators for f_p in absolute terms, obtain the desired performance indicators for the derived quantity, G_p .

3. Results and discussion

The previously presented models were proposed and adjusted by their authors for the hourly time scale, so they are not expected to perform as well with 1-minute data, which has significantly higher variability. This kind of comparison has been done before with diffuse fraction models (Engerer, 2015; Gueymard and Ruiz-Arias, 2016), investigating at which extent hourly models still hold or underperform when 1-min data is used. The result, of course, depends on the model.

Table 3 lists the original and locally adjusted coefficients for each model. The adjustments and performance of the original models is not only affected by the time scale of the data, but also by the typical local climate of the site and the characteristics of the data being used, so the original vs local parameter comparison is not straightforward. As a sanity check, it is noted that the sign of the parameters do not vary when locally adjusted and changes in their value are small, with the exception of the higher order terms of the ES model and the term associated with the solar altitude of the AL model.

Model	Parameters	a (µmol/J)	b (µmol/J)	c (µmol/J)	d (µmol/J)
AL	original	1.83	-0.19	0.10	
AL	locally adjusted	2.01	-0.26	-0.03	
TL	original	1.99	-0.07		
TL	locally adjusted	2.13	-0.04		
ES	original	2.73	-2.39	3.46	-1.56
ES	locally adjusted	3.04	-4.83	8.29	-4.70
TW	original	2.82	-1.54	0.56	
TW	locally adjusted	2.79	-2.07	1.48	
constant	Grossi et al. 2004	2.10			
constant	locally adjusted	2.19			

 Table 3: Original and adjusted coefficients for the PAR fraction models.

 Coefficient b in the TL model is dimensionless.

Table 4 presents the performance evaluation of the models with their original coefficients, including as a baseline the constant value $f_p = 0.4604 \times 4.566 \ \mu mol/J = 2.10 \ \mu mol/J$ (last row), obtained by Grossi Gallegos et al. (2004) for San Miguel, Argentina, a site located about 370 km from the LES site used for this work. The local version is the average PAR fraction obtained from our filtered dataset. They differ in about 4%, which is similar to the uncertainty in the data. The relevant performance metrics for each model (both original and locally adjusted) are given in Table 4. As expected, the constant models are among the worst in terms of RMSD.

When the original models are considered, all of them fall in a narrow range: relative MBDs between 4 and 7 % and RMSDs between 8 and 11%. The hourly-adjusted polynomial

models TW and ES (Tsubo and Walker, 2007; Escobedo et al., 2006) with their original coefficients provide the best local performance for 1-minute data, showing the lowest bias and dispersion. The second order polynomial of Tsubo and Walker performs slightly better, probably due to a higher robustness (polynomial instability increases with its order, specially for extrapolations). The original Alados et al. model comes third in performance, quite close to the first two in terms of rRMSD, but with higher bias (indeed, the worst bias). The Tiba and Leal model with original coefficients does not improve on the utilization of a constant value for the PAR fraction, nor in bias or dispersion. The polynomial models of Eqs. (3) and (4) with their original coefficients are the ones which better represent the local data and, therefore, are the recommended original models for the region.

Table 4 also presents the performance of the models with local adjustment. When the models are locally fitted, the analysis changes. The range of RMSDs is now between 5 to 10%, with negligible biases and all local models outperform the local constant value, as expected (they include extra variables with some predictive power). However, it observed that the Tiba and Leal model only improves the constant value to a small extent, hence the solar altitude as the single input variable seems to be inadequate for this problem. The models that use k_t as input show the higher improvements with respect to the local constant value. The locally adjusted model AL based on $log (k_t)$ is the best local model, followed by the polynomial k_t models ES and TW.

Model	Parameters	rMBD (%)	rMAD (%)	rRMSD (%)
AL	original	-6.9	7.0	9.2
AL	locally adjusted	0.0	3.3	5.4
TL	original	-5.3	6.5	11.5
TL	locally adjusted	-0.2	6.1	10.2
ES	original	3.8	6.0	8.0
ES	locally adjusted	0.0	3.3	5.6
TW	original	-0.8	6.0	7.9
TW	locally adjusted	0.0	3.8	6.3
constant	original	-3.3	6.0	10.9
constant	local	0.0	6.5	10.4

Table 4: Performance evaluation of the original models. The average for the relative metrics is 2.191µmol/J.

Figure 3 shows the dataset for PAR fraction vs k_t with the estimates from the original (violet) and the locally adjusted (red) models superposed. The PAR fraction at a 1 minute rate has an important enhancement for lower k_t values (cloudy conditions) and some locally adjusted models are not able to capture this feature in spite of their good performance metrics.

As Fig. 3c and 3e show (TW and ES models), the locally adjusted polynomial models are unable to adequately represent the variability of the 1-minute PAR fraction data, having acceptable overall metrics at the cost of misrepresenting data for either low or high k_t values. In particular, important deviations are observed for high k_t values (clear sky) in both polynomial models. On the other hand, the locally adjusted AL model (Fig. 1b) adequately

represents the PAR fraction tendency over the whole range of k_t . Finally, it is also observed that the constant value and the TL model are not able to reproduce the PAR fraction enhancement under cloudy skies, and this fact explains their poor performance indicators.



Figure 3: PAR fraction as a function of kt (1-minute time basis). Filtered data is shown as gray dots. The original model predictions are in red and the local adjusted model's predictions are shown in violet.

4. Conclusions

A first assessment of PAR fraction models in Uruguay has been presented. Four pre-existing empirical models, developed originally for the hourly timescale, were implemented and evaluated, in their original and locally adapted versions using a 1-minute quality-controlled dataset with four years of PAR photon flux and GHI data for a single location, representative of the Pampa Húmeda region of south-east South America. The frequently used constant

value for PAR fraction has also been tested, as a baseline model. The conclusions of this work are summarized as follows:

- The average PAR fraction *fp* was found to be 2.19 µmol/J, which is only 4% above the previous value obtained for this region using indirect pyranometer-based measurements (Grossi-Gallegos et al. 2004).
- The hourly adjusted polynomial models of Escobedo et al. (2006) and Tsubo and Walker (2005) with their original coefficients represent reasonably well the local 1-minute PAR fraction data with mean biases which are -1% to 4% of mean f_p .
- Overall metrics are improved significantly by the local adaptation. In spite of this, for the TW and ES models, the local adjustment with 1-minute data is not able to represent the PAR fraction behavior for the whole range of clearness index. For this reason, their use in the region is not recommended at the 1 minute timescale. We tested higher degree polynomials (up to eight degree) and none of them was able to adequately represent the 1-minute PAR fraction behavior.
- The solar altitude as input variable provides marginal gains. The TL model, which uses only this variable, has no significant advantage over the constant model for 1-minute PAR fraction data.
- The best locally adjusted model was the one proposed in Alados et al. (1996). This model has a logarithmic dependence on the clearness index which adequately represents the 1-minute f_p behavior, especially its enhancement under overcast conditions. This was the best performing local model at the 1-minute time scale with RMSD of around 5% and negligible bias.

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Expert quality control of solar radiation ground data sets

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Abstract

Ground-based radiation measurements are required for all large solar projects and for evaluating the accuracy of solar radiation models and datasets. Ground data almost always contain low-quality periods caused by instrumental issues, logging errors, or maintenance deficiencies. Therefore, quality control (QC) is needed to detect and eventually flag or exclude such suspicious or erroneous data before any subsequent analysis. The few existing automatic QC methods are not perfect, thus expert visual inspection of the data is still required. In this work, we present a harmonized QC procedure, which is a combination of various available methods, including some that include an expert visual inspection. In the framework of IEA PVPS Task 16, these tests are applied to 161 world stations that are equipped with various radiometer models, and are candidates for an ongoing benchmark of irradiance datasets derived from satellite or weather models. Because the implementation of these methods by experts, and their subsequent decisions, might lead to different QC results, the independently obtained results from nine evaluators are compared for two test sites. The QC results are found similar and more stringent than purely automated tests, even though some deviations exist due to differences in manual flagging.

Keywords: solar irradiance, solar resource, quality control, quality inspection, visual inspection.

1. Introduction

Ground-based radiation measurements constitute the basis for solar energy projects and applications. Such measurements are required to evaluate and improve the quality of radiation data derived from satellite retrievals or numerical weather models, and to monitor the performance of solar installations, in particular. The availability of such data is necessary to reach the required accuracy in solar resource data for utility-scale solar projects and for many other applications in the realms of solar power plant operation, solar forecasting, etc. Ground-based data almost always contain periods of low quality and erroneous measurements caused by instrumental errors, maintenance deficiencies, or environment-related inadvertent issues. Therefore, a stringent data quality control (QC) procedure is needed to detect such erroneous (or potentially erroneous) data and ultimately exclude them in highaccuracy applications. QC methods of various kinds have been proposed, e.g., (Espinar et al. 2011; Long and Dutton 2002; Maxwell et al. 1993; Long and Shi 2008). Each one of them consists of a suite of automatic tests. However, automatic tests alone are insufficient as they typically miss certain types of errors and often mislabel valid data. In the vast majority of cases, an expert visual inspection step must be added to automatic QC to obtain the best possible results.

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In this work, a harmonized QC procedure is developed in the form of a "*best-of*" method based on a combination of a variety of tests that have already been published and widely recognized, while adding expert visual inspections. Such a QC method is required as an essential first step of an ongoing benchmarking exercise, in which the quality and accuracy of solar irradiance estimates derived from satellite imagery and atmospheric reanalysis are evaluated through preprocessed ground-based measurements. To be meaningful, the benchmarking results must be obtained by comparison with measurements having the lowest possible uncertainty, which can only be obtained after a rigorous QC. The benchmarking exercise is an ambitious project currently being carried out under the auspices of the International Energy Agency's PV Power Systems (PVPS) Task 16. The database of ground measurements consists of several years of data from 161 ground stations, most of which using thermopile pyranometers for global and diffuse horizontal irradiance (GHI, DIF) and an automatically tracked pyrheliometer for direct normal irradiance (DNI). In order to perform QC of such a large database, a group of solar radiation experts from Task 16 was gathered, and several radiometric stations were assigned to each participant. Their QC results may differ to a certain degree for different reasons; for instance, experts might have different opinions on what constitutes a bad data point, they might have varying experience with a specific instrument model or with unusual measurement situations, or, more pragmatically, coding errors may be inadvertently introduced in some cases.

This study reports on the exemplary results obtained by nine different evaluators using data from two radiometric stations selected randomly. The spread of expert-assisted QC results is established to quantify how much they differ from the automatic tests. This makes it possible to evaluate the specific impact of the expert decisions on the overall QC process. In turn, this can help determine to what extent expert assistance contributes to the quality of validation datasets and should be considered as either optional or necessary in practice. The evaluators implemented the QC method individually so that any difference in implementation can be traced back for further improvements and better documentation. The deviations of the results of different evaluators are then compared to the variation in the fraction of usable data for the 161 stations.

The improved QC methodology, including all automatic and visual tests, is presented in Section 2. Section 3 compares the results of the QC undertaken by nine evaluators using data from two randomly chosen stations. In Section 4, conclusions are drawn and a summary is provided.

2. QC Methodology

The QC methodology consists of a combination of tests selected from the literature. In addition to these automatic tests, the evaluators also reviewed and reported the available information on instruments, calibration, maintenance, and records of any special events at each station if such detailed information was available. The visual inspection of such a large database (686 station-years of 1-min data from 161 stations) was an important accomplishment of this QC exercise, at a scale never attempted before.

There are several sets of QC tests that were specifically designed for historic radiation databases, such as BSRN (Long and Dutton 2002), SERI QC (Maxwell, Wilcox and Rymes, 1993), QCRad (Long and Shi 2008), MESOR (C. Hoyer-Klick et al. 2008; Carsten Hoyer-Klick et al. 2009), ENDORSE (Espinar et al. 2011), RMIB (Journée and Bertrand 2011), or MDMS (Geuder et al. 2015). In these methods of the literature, the various tests use different limits for the three individual irradiance components—diffuse horizontal (DIF), direct normal (DNI), and global horizontal (GHI)— as well as parameters derived from these components together with additional quantities such as solar position angles or clear-sky irradiance. The types of limits are:

- physical possible limits
- rare limits
- extremely rare limits.

The existing QC tests have been compared and critically discussed by experts in the framework of IEA PVPS Task 16. Considering the diversity of monitoring stations currently existing in the world, separate methods have been devised, (i) for the ideal case when measurements of all three irradiance components (GHI, DIF, DNI) are available; and (ii) for the case when only two components are directly measured (GHI and DIF or DNI). The latter case is typical of remote solar resource stations that are equipped with a rotating shadowband irradiometer (RSI); see details in Sengupta et al. (2021).

The quality control procedure developed here consists of the combination of automatic tests and a detailed visual inspection performed by an expert. Each test generates a specific flag per timestamp. Each flag can take one of

three possible values: "data point seems ok", "data point seems problematic", or "test could not be performed". The latter situation can occur because of a missing timestamp/data or because the test conditions were not met, and thus the test could not be applied.

The visual inspection of the data is of importance to detect bad data and manually assign a specific flag. This step also includes checking the metadata, if available (logbook with maintenance schedules, issues found, calibration information, comments, etc.). Visual inspection can also help determine if the timestamps refer to the start or the end of the averaging interval (e.g., 1-min, 10-min or 1-h averaging), since this information is not always provided in practice (or can be erroneous). The correct interpretation of the timestamps is essential for practically all QC tests but also for any validation or benchmarking exercise. Furthermore, errors in the correct time zone and coordinates can also only be identified through visual examination by an expert.

The applied QC tests are defined and described in detail below. All test results are visualized using appropriate public-domain software and provide automatically generated flags. Manual flagging is also permitted, thus providing a way to flag data that passed the automated QC tests. Some tests are not automated, but rather consist of purely visual inspections by the evaluators. The applied tests are:

- Missing timestamps
- Missing values
- K-Tests (Geuder et al. 2015; Gueymard 2017)
- BSRN's closure tests (Long and Dutton 2002)
- BSRN's extremely rare limits test (Long and Dutton 2002)
- BSRN's physically possible limits test (Long and Dutton 2002)
- Tracker-off test, improved from (Long and Shi 2008)
- Visual inspection, including shading assessment, closure test, AM/PM symmetry check for GHI, and calibration check using the clear-sky index.

All the automatic tests, as well as the visual review, are discussed in more detail in the following sections.

2.1 Missing timestamps

Skipped timestamps, which might occur during a data logger reset or data acquisition failure, are identified and filled in with the "not a number" date type (NaN). This ensures that, at the end of the QC procedure, all data files provide a continuous information flow.

2.2 Missing values

After filling missing timestamps with NaNs, the total number of missing data can be determined to give an overview of the data completeness of each station.

2.3 K-Tests

Various studies, e.g., (Geuder et al. 2015; Gueymard 2017), have defined a number of tests for physical limits and to detect possible tracker issues. These tests are based on the clearness indices K_n , K, and K_i , and their physical relationships. These quantities are defined as

$$K_n = \frac{\text{DNI}}{\text{ETN}} \qquad (\text{eq. 1})$$
$$K = \frac{\text{DIF}}{\text{GHI}} \qquad (\text{eq. 2})$$
$$K_t = \frac{\text{GHI}}{\text{ETN} \cdot \cos (\text{SZA})} \qquad (\text{eq. 3})$$

where ETN is the extraterrestrial irradiance at normal incidence, and SZA is the solar zenith angle. The suite of K-Tests is applied within each appropriate domain; the corresponding flag names are indicated in Tab. 1. If the condition is not fulfilled within the appropriate domain for one data point, the point is flagged with the corresponding flag name. Because the measured GHI at 1-minute resolution can be much higher than the corresponding clear-sky value during cloud-enhancement periods (Gueymard, 2017), the upper threshold for K_t is adjusted here for the use of 1-min data. It might have to be decreased somewhat for usage at 5-min or 10-min resolution.

Condition	Domain	Flag name
$K_n < K_t$	$(GHI > 50 \text{ W/m}^2 \text{ and } K_n > 0 \text{ and } K_t > 0)$	flagKnKt
$K_n < (1100 + 0.03 * ALT)/ETN)$	$(GHI > 50 \text{ W/m}^2 \text{ and } K_n > 0)$	flagKn
$K_t < 1.35$	$(GHI > 50 \text{ W/m}^2 \text{ and } K_t > 0)$	flagKt
<i>K</i> < 1.05	$(SZA < 75^{\circ} \text{ and } GHI > 50 \text{ W/m}^2 \text{ and } K > 0)$	flagKlowSZA
<i>K</i> < 1.1	(SZA \geq 75° and GHI $>$ 50 W/m ² and $K > 0$)	flagKhighSZA
K < 0.96	$(K_t > 0.6 \text{ and GHI} > 150 \text{ W/m}^2 \text{ and} $ SZA < 85° and <i>K</i> > 0)	flagKKt

Tab. 1: Performed K-Tests. ALT denotes the elevation of the site in m (a.m.s.l.).

2.4 BSRN's closure tests

To test the coincidence between the GHI, DNI and DIF irradiance components, i.e., any deviation from the ideal closure, the BSRN closure tests are applied (Long and Dutton 2002). If the conditions described in Tab. 2 are not fulfilled in the noted domain, the data point is flagged with the corresponding flag.

Tab. 2:	Performed	Three-Component	tests
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Condition	Domain	Flag name
$\left \frac{\text{GHI}}{\text{DNI} \cdot \cos(\text{SZA}) + \text{DIF}} - 1 \right \le 0.08$	(SZA \leq 75° and GHI > 50 W/m ²)	flag3lowSZA
$\left \frac{\text{GHI}}{\text{DNI}\cdot\cos(\text{SZA}) + \text{DIF}} - 1\right \le 0.15$	(SZA > 75° and GHI > 50 W/m ²)	flag3highSZA

2.5 BSRN's extremely rare limits test

The three irradiance components are also tested in comparison with extremely rare limits to flag any doubtful data (Long and Dutton 2002). If the condition for each component is not fulfilled for a data point, that point is flagged with the corresponding flag name, as described in Tab. 3.

Condition	Domain	Flag name
$-2 \le \text{GHI} \le 1.2 \cdot \text{ETN} \cdot \cos^{1.2}(\text{SZA}) + 50$	all data	flagERLGHI
$-2 \le \text{DIF} \le 0.75 \cdot \text{ETN} \cdot \cos^{1.2}(\text{SZA}) + 30$	all data	flagERLDIF
$-2 \le \text{DNI} \le 0.95 \cdot \text{ETN} \cdot \cos^{0.2}(\text{SZA}) + 10$	all data	flagERLDNI

2.6 BSRN's physically possible limits test

In addition to the extremely rare limits, the physically possible limits of each component are tested as well (Long and Dutton 2002). Considering the high-quality requirement for the benchmark application envisioned here, both tests are considered. If the condition for each component is not fulfilled for one data point, the point is flagged with the corresponding flag name (Tab. 4).

Tab. 4: Performed physically possible limits tests

Condition	Domain	Flag name
$-4 \leq \text{GHI} \leq 1.5 \cdot \text{ETN} \cdot \cos^{1.2}(\text{SZA}) + 100$	all data	flagPPLGHI
$-4 \le \text{DIF} \le 0.95 \cdot \text{ETN} \cdot \cos^{1.2}(\text{SZA}) + 50$	all data	flagPPLDIF
$-4 \le \text{DNI} \le \text{ETN}$	all data	flagPPLDNI

2.7 Tracker-off test

Since, for most stations, the direct and diffuse components are obtained with a tracker equipped with a pyrheliometer and a pyranometer with shading disc or ball, a tracker failure results in incorrect values for both measurements. Such failures include electromechanical problems within the tracker, loss of power, misalignment or timestamp error, etc. Detecting such problems is critical, but can be difficult, particularly in the case of slight mistracking. This specific test involves comparisons with rough estimates of the coincident clear-sky irradiance components (GHI_{clear}, DNI_{clear}, DIF_{clear}), which are here obtained as a fixed fraction of the extraterrestrial irradiance at horizontal incidence (Tab. 5). If all conditions described in Tab. 5 are not fulfilled for any data point, it is flagged with the corresponding flag name.

Condition	Definitions	Flag name
$\frac{(\text{GHI}_{\text{clear}} - \text{GHI}_{\text{measured}})}{(\text{GHI}_{\text{clear}} + \text{GHI}_{\text{measured}})} < 0.2$ $\frac{(\text{DNI}_{\text{clear}} - \text{DNI}_{\text{measured}})}{(\text{DNI}_{\text{clear}} + \text{DNI}_{\text{measured}})} > 0.95$ $\text{SZA} < 85^{\circ}$	$\begin{array}{l} \text{GHI}_{\text{clear}} = 0.8 \cdot \text{ETH} \\ \text{DIF}_{\text{clear}} = 0.165 \cdot \text{GHI}_{\text{clear}} \\ \text{DNI}_{\text{clear}} = \frac{\text{GHI}_{\text{clear}} - \text{DIF}_{\text{clear}}}{\cos(\text{SZA})} \end{array}$	flagTracker

Tab.	5:	Performed	tracker-off	tests
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2.8 Visual inspection with a multi-plot

All test results and selected irradiance data are compiled into a single multi-plot arrangement for easy visualization. Such a plot is made for each year at a single station (see, e.g., Fig. 1 for the Visby station, 2016). For a larger example image of the multi-plot please refer to <u>https://github.com/AssessingSolar/solar_multiplot</u>. More specifically, these plots not only include visualization of the test results discussed above, but also (1) visualization of the deviation of the pyrheliometer's DNI from the DNI calculated from DIF and GHI (i.e., closure error); (2) an overview of the diurnal variation of DNI and GHI as a function of time and solar position; (3) the clear-sky index calculated as the ratio between the measured GHI and the clear-sky GHI from the public-domain McClear v3's database (Lefèvre et al. 2013; Gschwind et al. 2019; Qu et al. 2017); (4) a comparison of the pyranometer GHI measurement to the GHI calculated from DNI and DIF; and (5) comparisons of the pyranometer GHI measurements before and after solar noon to identify possible levelling or timestamp errors; (6) visualization of the data points in *K*-space with the applied limits.



Fig. 1: Visualization of various QC tests used to evaluate the quality of irradiance data at one station (Visby, Sweden, 2016). Numbers in boldface refer to the description in the text.

A multi-plot like the one shown in Fig. 1 is created not only from the raw (pre-QC) data, but also from the data that pass the automatic flagging (as an intermediate result for additional scrutiny), and data that pass the complete QC including manual revision. If suspicious data points are found, further visualizations can be used to confirm whether those points are invalid, in which case an overriding manual flag is set that can be used to exclude such points from processing. For each station and year, the three multi-plots just described offer a complete overview

of the station data and help with the identification of suspicious data or time periods. They serve as a solid starting point for the final manual review.

Plot (1) in Fig. 1 shows the deviation between the measured and calculated DNI with respect to the sun's azimuth angle. In this case, two distinct levels appear over the year. To detect if a specific issue existed at the station (e.g., long periods without cleaning or of tracker issue), one needs further visualization of the data. One example is shown in Fig. 2, which describes the diurnal variation of DNI for each day of a complete year. The day of the year appears on the x-axis, whereas the time of day is shown vertically, using *true solar time* to emphasize the expected symmetry around solar noon. The left plot shows a clearly different deviation pattern in the later part of the year (black rectangle). This is not a station issue per se, but the result of a sensor change. This resulted in a slightly different year. It shows a change in deviation caused by sensor soiling, which remained over a long period. While the sensor changes in Fig. 2-left do not lead to an exclusion of the data, the sensor soiling shown in Fig. 2-right can lead to data exclusion. This demonstrates the necessity of manual expert quality control and the general need for station log books, in which cleaning intervals and sensor changes are to be recorded.

The clear-sky index time series (3) is helpful to reveal whether the GHI sensor's calibration is outdated or its sensitivity drifts over time. Ideally, the clear-sky index would be equal to \approx 1 under clear-sky conditions. This is rarely the case in the real world, however. (One reason is that GHI_{clear} is only an approximation at any instant.) Nevertheless, cases where the clear-sky index remains constant and well below 1 can be an indication of calibration issue. Similarly, an abrupt or step-like change in that value under clear conditions is typically the signature of a change of calibration factor by a substantial amount. Again, an expert is needed to decide whether a calibration issue is likely at the station. In Fig. 1, the clear-sky index is constant and well below 1 in the later part of the year, but this is the result of cloudy weather conditions rather than a calibration issue. This is apparent when comparing the heat maps of GHI and DNI (plot (2) in Fig. 1), which are placed just above the clear-sky index plot.

If the expert detects issues with individual data points, those are flagged with "flagManual". The results of the individual tests, in the form of a quality flag per test, are properly documented (metadata) and packed into one single file per site and year, which also includes the solar irradiance observations. Finally, all flags are combined into a single usability code, indicating an objective level of quality for each data point.



Fig. 2: Two heat maps in W/m² of the difference between DNI measured and DNI calculated on axes of hour of the day (y-axis) and day of the year (x-axis) for different station years. Left: Visby 2015; Right: Visby 2019.

2.9 Usability of a data point

To decide if a data point should be used in any subsequent analysis, not only the result of a single flag per timestamp is needed, but all flags for that timestamp and surrounding timestamps must be considered. For the validation of satellite-based irradiance estimates, and of model-derived radiation data in general, the following procedure is recommended, because it ensures that any data point that passed a test just by chance is excluded from further analysis. Ultimately, a data point is declared "usable" if either it passed all individual QC tests or the test could not be performed while all measured radiation components were available. Moreover, if 30% or more of the timestamps during daytime (i.e., solar elevation >0) from one day are flagged, the entire day is excluded in order to avoid data islands that passed the QC by chance. Intervals between flagged data that are shorter than 60 min are also excluded. For the determination of the length of the interval, only timestamps for sun-up instances are considered. In the case of missing timestamps or missing data in general, the data points are also considered not usable. These applied exclusion rules are quite strict as we exclude for example GHI data for a time stamp although maybe only the DNI measurement was erroneous and as we apply the above described additional rules

to avoid data islands. Less stringent exclusion rules could be applied for other purposes, such as the determination of monthly or yearly sums. These calculations are critically important in solar resource applications, but are often affected by data breaks caused by missing or bad data points. To circumvent this issue, the method outlined in Salazar et al. (2020) is recommended.

3. Results obtained by the nine evaluators

In order to evaluate the influence of the expert decisions and possible variance in the implementation of the method on the QC results, all nine evaluators independently performed their own analysis for the same two stations, Visby (Sweden) and Cairo (Egypt), using five and six years of data, respectively.

3.1 Results for Visby

An overview of the evaluation results for Visby are shown in Fig. 3 as the fraction of flagged sun-up data. The fractions include the flags from automatic tests and manual flagging. The lowest fractions are hence not zero even if an evaluator did not flag any data manually as at least some data points are typically flagged automatically. If at least one test is flagged as non-passed, the timestamp is counted as flagged, i.e., not usable. In terms of total data points being flagged, the overall results show that some evaluators rejected slightly more data than others. In particular, Evaluators 3 and 4—and to a lesser degree, Evaluator 5—were typically much less conservative than the others. The manual flags resulting from the (subjective) visual tests are the cause for these small discrepancies. The overall fraction of flagged data at the Visby station is comparably low.

	flagged_2015	flagged_2016	flagged_2017	flagged_2018	flagged_2019
Eval_1	0.35%	0.61%	0.40%	0.38%	0.28%
Eval_2	0.45%	0.75%	0.52%	0.45%	0.35%
Eval_3	0.16%	0.33%	0.20%	0.20%	0.16%
Eval_4	0.12%	0.38%	0.20%	0.18%	0.14%
Eval_5	0.33%	0.25%	0.30%	0.34%	0.26%
Eval_6	0.51%	0.91%	0.58%	0.44%	0.33%
Eval_7	0,34 %	0.61 %	0.39 %	0.37 %	0.27 %
Eval_8	0.36%	0.60%	0.40%	0.37%	0.28%
Eval_9	0.39 %	0.97 %	1.12 %	0.41 %	0.30 %

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3.2 Results for Cairo

A similar plot as Fig. 3 is shown in Fig. 4 for the Cairo station, which has been installed within the framework of the enerMENA project (Schüler et al. 2016; Hassan et al. 2021). Here, a larger fraction of data points was flagged by all evaluators, and moreover the deviations between different evaluators are higher. Still, Evaluators 3–5 remain the least conservative of them all. The automatic flags accessed by the different evaluators are again the same, so that the deviations are only caused by manual flagging. In the case of year 2016 in particular, Evaluator 1 flagged nearly 5% more data than any other evaluator. The main reason for this has been traced back to a number of temporally short, but periodically occurring shading events caused by objects near the radiometers. After further investigation, the cause of this periodic shading was found to be two guy cables of the windmast at about 5 and 10-m height. They could not be positioned better during the station setup because of space limitations, so that shadows unfortunately appear each morning about half of the year. Considering the short duration of the shading events and the subsequent normal appearance of the DIF, GHI and DNI signals, some evaluators decided to flag longer intervals containing several short shading events, whereas others only flagged individual shading events. It is also possible that some short shading events were not detected, at least by some of the evaluators, even with the automatic tests and the visual inspection. During 2016, short power outages also occurred, explaining why the highest deviations and the highest fractions of flagged data appear in 2016.

The additional exclusion of intervals between flags of less than one hour explains why the effect of these deviations between evaluators are partly removed with the "usability" property of a data point. To avoid missing short intervals with bad data, and to obtain an efficient manual data quality control, flagging longer intervals can be useful. Fewer valid data points then remain, however. Depending on the application of the data, both options can be adequate because rejecting data is a trade-off between the remaining size of the data set and its quality.

	flagged_2015	flagged_2016	flagged_2017	flagged_2018	flagged_2019
Eval_1	3.68%	11.37%	7.38%	3.80%	6.68%
Eval_2	1.69%	6.01%	5.73%	2,73%	5.20%
Eval_3	0.87%	2.35%	2.22%	1.08%	2.04%
Eval_4	0.67%	2.14%	2.10%	1.03%	1.94%
Eval_5	0.99%	3.24%	3.32%	1.51%	2.94%
Eval_6	3.19%	6.92%	5.22%	2.78%	5.20%
Eval_7	2.29%	6.70%	7.01%	3.67%	6.69%
Eval_8	1.63 %	6.04 %	5.63 %	2.72 %	5.22 %
Eval_9	1.44%	4.74%	4.74%	2.62%	5.08%

Fig. 4: Comparison of QC results from nine evaluators for Cairo, showing the number of flagged 1-min data points in percent

As a general rule, it is found that the manual tests operated by an expert can substantially decrease the number of invalid data points in comparison with using automated tests only, and thus decrease the overall uncertainty of a measured dataset. This reduction of the overall uncertainty is the result of excluding the most uncertain data points which might be caused by extraordinary levels of sensor soiling, shading events or sensor malfunction. This operation relies on substantial expertise and takes time, however, and can therefore induce substantial costs in practice.

3.3 Results for the whole database

From a different perspective, the significant deviations found between the rejection rates from different evaluators should also be gauged according to the actual deviations between the usable data for different stations. In the data set of 161 stations used in this study, the whole range from 0 to 100% flagged data points is actually covered in great part, depending also on month and year. To show this more clearly, the fraction of usable data per station and year is analyzed for each continent. The location of the stations, and their total number for each continent, appear in Fig. 5. The database is partly obtained from the Southern African Universities Radiometric Network (Brooks, M.J. et al. 2015), the National Renewable Energy Laboratory (Andreas and Stoffel 1981; Andreas and Wilcox 2012; 2010; Andreas and Stoffel 2006; Vignola and Andreas 2013; Ramos and Andreas 2011), the Baseline Surface Radiation Network (Driemel et al. 2018; Gueymard et al. 2022), and further sources.



Fig. 5: Map of tested ground stations. The color bar shows the number of years that are used at each station. Source of world map: (Stöckli et al. 2005).

The color of each data point corresponds to the number of calendar years under scrutiny, from one to six. For each station, the maximum period considered in the QC exercise is from 2015 to 2020, inclusive. (Many stations are recent and reported data only between 2015 and 2020, which is why no earlier period was considered for consistency.) The fraction of usable data per year can be seen in Fig. 6, where the average number of usable data

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points per year and station is shown as a boxplot for groups of stations within each continent. Only the usable sunup data points are counted after considering missing data, flags, and the removal of "data islands" (i.e., short periods between flagged data points). The lower and upper quartiles are marked with a box, whereas the full range of the results is marked by whiskers. The star symbol marks the average, and the red line marks the median. The average number of usable data points in each group is very different, and so are the dispersion and the interquartile range. Note that the spread and the interquartile range are also impacted by the number of stations and years within each group. In summary, the covered range of usable data points is relatively large, and varies roughly between 20% and 90%. As could be expected, the usable fraction is consistently low in Antarctica because of the harsh conditions.



Fig. 6: Box plots of the fraction of usable data points per station and year, grouped by continent. The number of stations per continent and the corresponding total number of calendar years is indicated as well.

Because of time constraints, almost all stations were only evaluated by a single evaluator. In those cases, a detailed comparison similar to that described above for Visby and Cairo is not possible. Nevertheless, the evaluators' results were analyzed on a continental basis in order to at least roughly check for obvious strong deviations that would have been introduced by their manual flagging. Tab. 6 indicates which fraction of stations within each continent was evaluated by each evaluator. Interestingly, Evaluator 1 contributed a number of North American stations that is comparable to that of Evaluators 3–5, but systematically flagged more data than them in the comparison for Visby and Cairo (see Fig. 3 and Fig. 4). The interquartile range and the spread of usable data points for the North American stations are small, as shown in Fig. 6. This does not indicate a too high number of flags by any one of the four main evaluators for North America. Of course, this does not prove that there is no bias in judgment, because the stations tested by Evaluator 1 might have been the most "reliable" stations by chance. In any case, the small spread and interquartile range suggest that the deviation that exists between the results from different evaluators is small compared to the overall variation in data quality.

Tab. 6: Distribution of stations evalu	ated by each evaluator for each continent.
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Evaluator	Africa	Antarctica	Asia	Australia	Europe	N. America	S. America
Eval_1	2%	-	2%	-	-	23%	100%
Eval_2	5%	-	-	-	55%	-	-
Eval_3	-	67%	2%	94%	9%	23%	-
Eval_4	-	-	-	-	-	26%	-
Eval_5	-	-	14%	-	9%	26%	-
Eval_6	19%	-	36%	-	17%	-	-
Eval_7	24%	-	29%	-	5%	-	-
Eval_8	7%	33%	17%	6%	5%	2%	-
Eval_9	43%	-	-	-	-	-	-

4. Conclusion and Outlook

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A stringent QC method based on expert consensus was developed based on various tests from the literature, after discussion among a group of international solar radiation experts who participate in IEA PVPS Task 16. The proposed QC method incorporates a suite of up to 15 specific tests, depending on the measurement principle (three independent irradiance components, or only two), and multi-plots describing key variables and covering a whole year of data at each site. The method was successfully applied to 161 radiometric world stations, using up to six years of data per station.

The automated and expert-augmented QC results were compared for two exemplary stations, Visby and Cairo, totaling 10 years of data. The results obtained independently by nine evaluators showed deviations caused by differences in manually set flags, i.e., in their judgment of why a data point should be considered bad or highly suspect. For the Visby station, only few data points were manually flagged, and the evaluators flagged nearly the same data points. In contrast, for the Cairo station, more data points were manually flagged, and the deviation between the different evaluators was much higher. The main reason for this marked deviation was eventually identified as an intermittent shading issue caused by unusual constraints in the station's design. It is expected that such deviations between expert results are small enough in general to not negatively impact demanding applications, such as the radiation data benchmark currently undertaken by the same experts. The deviations could most likely be reduced further if clearer criteria for manual rejection would be defined.

The deviations of the manually flagged data points were also compared to the usable fraction of data produced by the QC procedure for the 161 stations under scrutiny. The deviations between the fraction of data manually flagged by the nine evaluators were found much lower than the station-to-station deviation of the fraction of usable data. This tends to confirm the applicability of the proposed QC method.

An important conclusion is that the visual checks made by experts can substantially improve the quality of a measured dataset and decrease its uncertainty. This suggests that automated tests cannot currently detect all sources of erroneous data. The noted deviation in the manual assignment of quality flags illustrates the inherent subjectivity in discerning whether a data point appears usable or not. In spite of this, not applying any expert-based visual inspection or data control can result in a significant number of overseen erroneous data points, which would be detrimental. Another important conclusion is that further research on even more sophisticated automatic quality control methods would be needed to reduce the effort and costs involved by expert data QC. This could also lead to a lower subjectivity of the quality control.

The QC code is publicly available in order to provide a reference QC tool for researchers and the whole solar industry under this address <u>https://github.com/AssessingSolar/solar_multiplot</u>. For a number of stations used in this study, the quality controlled data including the individual flags is publicly available under this address <u>http://dx.doi.org/10.23646/3491b1a6-e32d-4b34-9dbb-ee0affe49e36</u>

The presented QC procedure constitutes the first step of a benchmark of modeled irradiance data sets that is currently being carried out by experts within IEA PVPS Task 16. The results of that study will be reported subsequently.

5. Acknowledgments

The authors would like to thank NamPower in Namibia, Yuldash Solirov from the Institute of Material Science in Uzbekistan, Frank Vignola from the University of Oregon, David Pozo from the University Jaen, Dietmar Baumgartner from the University of Graz, Julian Gröbner at PMOD, Nicolas Fernay from the University of Lille, Peter Armstrong at the Masdar Institute, Laurent Vuilleumier at MeteoSwiss, Irena Balog at ENEA, Sophie Pelland at CanmetÉNERGIE Varennes, Etienne Guillot at CNRS-PROMES Odeillo, and Majed Al-Rasheedi at the Kuwait Institute for Scientific Research for the provision of data for this study. Furthermore, we gratefully thank the Department of Civil Engineering at the Technical University of Denmark, the Swedish Meteorological and Hydrological Institute, the Australian Government Bureau of Meteorology, the INPE National Institute of Space Research, the CCST Center for Earth System Sciences, along with FINEP Financier of Studies and Projects Ministry of Science and Technology, PETROBRAS Petróleo Brasileiro, the SKYNET organization (in particular Hitoshi Irie and Tamio Takamura (CEReS/Chiba-U.), Chiba University, Tadahiro Hayasaka (Tohoku University), and Chulalongkorn University), as well as the ESMAP program of the World Bank Goup (in particular Joana Zerbin, Clara Ivanescu, Branislav Schnierer, Roman Affolter, GeoSUN Africa, Rachel Fox, and Margot King), the NOAA Global Monitoring Laboratory and the BSRN (in particular for stations 1, 3, 4, 6, 7, 8, 9, 10, 11, 13, 17, 20, 21, 31, 32, 33, 34, 35, 36, 37, 40, 42, 45, 47, 48, 49, 53, 56, 57, 58, 59, 60, 61, 63, 65, 70, 71, 72, 74). We would also like to thank the German Federal Foreign Office for funding and coordinating the enerMENA project., and to express our deep gratitude to the other project partners for their efforts in measuring the meteo-solar data and for agreeing to share their data. These partners are the Cairo University in Egypt, the University of Oujda and Institute Research Solar Energy et Energies Nouvelles (IRESEN) in Morocco, the Research and Technology Centre of Energy (CRTEn) in Tunisia, the University of Jordan in Jordan, and the Centre de Developpement des Energies Renouvelables (CDER) in Algeria.

CSPS and DLR thank the German Ministry for Economic Affairs and Energy for funding their contribution to the study within the SOLREV project (contract number 03EE1010). Adam R. Jensen thanks the Danish Energy Agency for funding his participation (grant number: 64019-0512). Part of this work has been financed by Research Fund for the Italian Electrical System with the Decree of 16 April 2018.

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A Comparison of Time Series Gap-Filling Methods to Impute Solar Radiation Data

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Abstract

Complete solar resource datasets play a critical role at every stage of solar project phases. However, measured or modeled solar resource data come with significant uncertainties and usually suffer from several issues, including but not limited to, data gaps, data quality issue, etc. In order to mitigate these issues an appropriate data imputation method should be implemented to build a complete and reliable temporal (and spatial) database. Being motivated by this, in this study we compare the performances of eight different gap filling methods extensively by creating random and artificial data gaps in (i) hourly irradiance data for one year using a few locations of the National Solar Radiation Database (NSRDB) and (ii) one-minute ground measurement dataset from Surface Radiation Budget Network (SURFRAD) and the National Renewable Energy Laboratory (NREL) stations.

Keywords: Global horizontal irradiance, clearness index, time series, gap fill

1. Introduction

In recent years, due to significant technological improvements in different cost competitive PV systems, accurate and complete solar resource data have become essential for predicting the solar energy output of these conversion systems and in reducing the expense associated with mitigating performance risks. However, solar resource data are prone to data gaps (missing data) due to instrument malfunctions, discarded data due to data quality problems and/or human error or satellite issue in terms of modeled satellite derived solar resource data. Therefore, from a practical point of view, it is of primary importance to fill those data gaps in order to make the data useable. In this study we apply different existing statistical temporal gap-fill methods to both measured and modeled datasets. In particular, here we consider (a) the ground measurement data from seven National Oceanic and Atmospheric Administration Surface Radiation Budget Network (SURFRAD) and NREL stations and (b) the modeled data from the National Solar Radiation Database (NSRDB V3). Furthermore, in this study, we restrict our attention to the solar irradiance data and other meteorological inputs to gap-fill natural and artificial data gaps.

2. Methodology

One year of data (2017) was obtained from the NSRDB and the ground measurement from SURFRAD and NREL sites (Figure 1) which contain the following three components for solar irradiance - global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) - as well as related meteorological parameters (Augustine et al. 2000, Sengupta et al. 2018). Further, the NSRDB data are available at thirty-minute intervals and the associated GHI time-series are occasionally incomplete, containing varying gap sizes. To reduce the scale of values between 0 and 1 and to remove the effects of low sun angle, in this study we consider clearness index Kt (GHI normalized by extraterrestrial radiation). We also consider the clearness index Kt, for ground-based measurements at one-minute resolution from NOAA's SURFRAD and NREL locations. In Section 2.1 we briefly describe the different imputation methods considered in this study to fill missing Kt values followed by descriptions of different metrics we use to compare their relative performances. The statistical metrics used are described in Habte et al. (2017).



Fig. 1: NOAA SURFRAD and NREL locations over United States climate regions (modified from Habte et al., 2017)

- 2.1 Different gap-filling methods
- a) Kalman filter and smoothing for structural times series Kalman filtering, also known as linear quadratic estimation (LQE), is a recursive algorithm that produces missing values of a univariate time series by estimating a joint probability distribution over the variables for each timeframe. The structural time series models can be viewed as regression models in which the predictors are a function of time and the parameters varying with time.
- b) Kalman filter and smoothing for state space representation of an autoregressive integrated moving average (ARIMA) model In this method, Kalman filtering is applied to the most popular parametric class of nonstationary time series, namely, Autoregressive Integrated Moving Average (ARIMA) model, which primarily uses several lagged observations of time series to forecast observations.
- c) *Linear interpolation* Linear interpolation, the simplest and probably the most widely used curve-fitting method, uses a straight line between two points for interpolation.
- d) *Spline interpolation* Spline interpolation uses a similar approach as in the linear interpolation, except the interpolant is now constructed using a piecewise polynomial function, commonly known as splines.
- e) *Stine interpolation* Stine interpolation can be considered as an extension of the linear and spline interpolation methods, where the interpolant uses piecewise rational interpolation to construct data points within a curve.
- f) *Simple moving average* In time series, simple moving average (SMA) is defined as the unweighted mean of an equal number of data on either side of a central value.
- g) *Linear weighted moving average* In this method, instead of unweighted mean as described in SMA we use a weighted mean of the observations, where weights decrease in arithmetical progression. For example, the observations directly next to a central value, have weights 1/2, the observations one further away have weights 1/3, and so on.
- h) Exponential weighted moving average An exponential weighted moving average calculates the weighted

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mean where the weights decrease exponentially. For example, the observations directly next to a central value, have weights 1/2, the observations one further away have weights 1/4, the next have weights 1/8, and so on.

Additional methods examined include: last observation carried forward, next observation carried backward, mean value, and random sample. These methods were excluded during preliminary trials due to applicability issues for time series and high deviations of the resulting statistical metrics. Furthermore, gap-filling methods that adjust for a seasonal component were also examined, such as seasonally decomposed and seasonally split missing value imputation. However, these methods were also excluded due to no presence of seasonality within the NSRDB or ground-measurement derived Kt series.

2.2 Data Pre-Processing

Before imputing on the NSRDB data for each location, two data pre-processing steps were implemented as follows:

- Use data when solar zenith angle is less than 80°. Remove the first four rows of missing values (denoted by NA) from each data set.
- The NSRDB is a serially complete dataset with missing data being filled through interpolation. Fill flags with non-zero values identify the filled points. Where the fill flag variable does not equal zero, we set the corresponding *Kt* observation to missing. Note that, the fill flag variable indicates missing data for values other than zero due to following conditions: 0: no fill; 1: missing cloud type; 2: full time series missing cloud type; 3: missing cloud property; 4: full time series missing cloud property; 5: GHI exceeds clear sky; 6: missing irradiance.

For the ground-based measurements, the following pre-processing step was applied:

• Remove nighttime Kt observations corresponding to a solar zenith angle measurement greater than 89.5%

2.3 Creating Artificial Gaps

In order to measure the performance of the eight imputation methods, artificial gaps were created in both the NSRDB and ground measurement data. The NSRDB data contains missing data points due to missing satellite measurements whereas the ground measurements are complete and without data gaps.

2.3.1 NSRDB Data

To create synthetic gaps in the NSRDB data, the occurrence of gap sizes was examined for each location.



Occurrence of gap sizes

Fig. 2: Distribution of consecutive NA gap sizes and number of occurrences for the Bondville, IL NSRDB data

Figure 2 shows both the number of occurring gap sizes (red) as well as the total resulting NAs for the gap size (blue) for the Bondville, IL NSRDB location. For example, a consecutive NA gap size of 4 occurs approximately 180 times resulting in a total of over 600 NA values. Additionally, a gap size of 48 consecutive NAs occurs once, totaling 48 NA values. Artificial gaps for the NSRDB data were created using a random sampling of the corresponding location's NA distribution.

2.3.2 Ground-measurement Data

All missing values in the measured data were synthetically removed. The same distributions of the original missing values in the NSRDB data were used; however, as the ground measurements are in one-minute intervals, compared to the NSRDB measurements in 30-minute intervals, the missing data lengths were multiplied by a factor of thirty. For example, the creation of one consecutive NA gap size in the NSRDB data corresponds to the addition of a thirty consecutive NA gap size in the ground measurement data. Note that the distributions used for the ground measurement data locations align with the corresponding NSRDB location.

2.3 Statistical Reporting Metrics

As mentioned earlier, in order to measure the performance of different imputation methods listed above, we create synthetic gaps in the Kt series using the distribution of missing (NA) values for NSRDB locations over the SURFRAD and NREL sites. Note that, in order to apply the same distribution to the ground measurements which are obtained in one-minute intervals, each distribution value was multiplied by thirty as previously mentioned. After applying different gap-filling methods to the same datasets, the following criteria, namely, Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and MAE percent of reading (%), and Mean Bias Error (MBE) are calculated for each site as described in Habte et al. (2017). The resulting equations are listed below , where N corresponds to the number of data, ytrue is the actual value of Kt at time t, and yi corresponds to the imputed Kt value at time t.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - y_{true}))^2}$$
 (eq. 1)

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |y_{true} - y_i| \qquad (eq. 2)$$

$$MBE = \frac{1}{N} \sum_{i=1}^{N} (y_i - y_{true})$$
 (eq. 3)

3. Results

3.1 NSRDB Data

To further measure method performance, the strings of consecutive NA values in the NRSDB *Kt* series, both originally missing and synthetically created gaps, were partitioned into varying bin sizes. Each method's imputation performance is measured for all six NA bin sizes across three separate groups, namely, (1) Bin 1: 1 consecutive NA's, and (2) Bin 2: >1 consecutive NA's, (3) Bin 3: 1-2 consecutive NA's, (4) Bin 4: >2 consecutive NA's, (5) Bin 5: 1-3 consecutive NA's, (6) Bin 6: >3 consecutive NA's. Dividing the bin sizes into three separate groupings allowed for testing the sensitivity of the imputation methods to gap size. For example, in the figures discussed below, it is concluded that spline interpolation's imputation performance significantly suffers when implemented on large gap sizes.

Figure 3 shows the RMSE results for each method and bin size for the Bondville, IL NSRDB site. Spline interpolation performs significantly worse in imputing the missing values for bins 2, 4, and 6 compared to the other methods. Kalman filter methods, linear and stine interpolation, and the moving average methods perform similarly for all bin sizes except bin 2 in which stine interpolation has a low RMSE value comparatively.



Fig. 3: Resulting RMSE values by imputation method across six NA bin sizes for Bondville, IL NSRDB data

Figure 4 shows the resulting MAE for each method and bin size for the same NSRDB location. Like with RMSE, spline interpolation is the worst performing imputation method. In the case of MAE, there is more difference between the other imputation methods, with the Kalman filter and moving average methods performing most similarly.



Fig. 4: Resulting MAE values by imputation method across six NA bin sizes for Bondville, IL NSRDB data

Both linear and stine interpolation has the smallest MAE values across all six bin sizes. The values between these two interpolation methods are not statistically different.

Figure 5 shows the resulting absolute values of the MBE results for each imputation method and across the six bin sizes. For graphical purposes, the absolute value was used to visually compare the bias across the methods. Like with RMSE and MAE, spline interpolation has the highest bias across bins 2, 4, and 6. The method also has noticeable higher bias than the other for bin 1. Stine interpolation and the moving average methods exhibit the lowest bias; however, the Kalman filter methods and linear interpolation do not have significant higher bias comparatively. From the statistical metrics shown above and those for the other NSRDB locations, we conclude linear interpolation and stine interpolation are the best performing methods with low RMSE, MAE, and MBE values across all bin sizes. We have also shown that all methods except for spline interpolation are relatively insensitive to change in consecutive NA gap size. As expected, the resulting statistical metrics increase as gap size increases.



Fig. 5: Resulting absolute MBE values by imputation method across six NA bin sizes for Bondville, IL NSRDB data

3.2 Ground measurement Data

While gap filling the NSRDB data sets, the imputation methods were tested for both prediction performace and sensitivity to numerous NA gap sizes. For the SUFRAD data, six bin sizes were also used to calculate the resulting metrics according to consectuive NA gap sizes. Note that only one trial was run with all siz bin sizes compared to three separate groupings in the NSRDB data. Additionally, only linear and stine interpolation methods were applied to the ground measurement data as follows the NSRDB results. To account for the difference in measurement intervals between the NSRDB and SURFRAD data, the NSRDB NA distributions were multiplied by thirty for their corresponding SURFRAD sites. The converted bins are (1) Bin 1: 1-30 consecutive NA's, (2) Bin 2: 31-60 consecutive NA's, (3) Bin 3: 61-90 consecutive NA's, (4) Bin 4: 91-120 consecutive NA's, (5) Bin 5: 121-150 consecutive NA's, and (6) Bin 6: >150 consecutive NA's.

Figure 6 shows the resulting RMSE for the ground measurement data by location and interpolation method across all six bin sizes. For each location and bin size, linear interpolation has the smaller resulting RMSE, though, these values do not significantly differ for stine interpolation. The methods perform most similarly for the DRA location, which has more clear sky days and, therefore, less missing observations compared to the other locations. We expect the locations with larger NA distributions to result in higher RMSE values.



Fig. 6: Resulting RMSE by location and interpolation method for ground measurement data

Figure 7 shows the resulting MAE across all six bin sizes by location and interpolation method for the ground measurement data. Linear interpolation has smaller resulting MAE for locations BON, FPK, and PSU. The methods perform similarly across bin sizes for locations DRA, GWN, and SXF. Stine interpolation has smaller resulting MAE for location NREL. We see that the methods are performing closely in terms of MAE and vary in performance based on location, though, the values are not significantly different.



Fig. 7: Resulting MAE by location and interpolation method for ground measurement data

Figure 8 above shows the absolute MBE values per bin size across interpolation methods and location. As

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mentioned for the NSRDB results, the absolute value of MBE was taken for graphical comparison purposes since we are focused on observing how far the value is from zero. Unlike the RMSE and MAE results, the resulting MBE greatly varies across bin sizes, interpolation method, and location. As expected, a higher bin size (larger length of consecutive NA's) results in a higher bias among the imputed values. There is not consistently low bias across bin sizes per location. For example, linear interpolation has a higher bias for bin 2 at the DRA location compared to stine interpolation but has a lower bias for the same location for bin 3. The two methods exhibit an array of biases.



Fig. 8: Resulting MBE by location and interpolation method for ground measurement data. Note: for plotting simplicity, absolute values of the MBEs are considered in this figure.

4. Conclusion

Appropriate usage of solar resource dataset for solar energy project phases depends largely on the completeness of the dataset. This study evaluated eight statistical imputation techniques and selected and implemented two of them to fill NSRDB and ground measurement random and artificial data-gaps.

As described in the results, linear and stine interpolation outperformed the other six imputation methods in terms of RMSE, MAE, and MBE for each NSRDB location across three groupings of two differing NA gap sizes. Hence, when imputing the ground measurements, only linear and stine interpolation were applied. The two perform similarly in terms of RMSE and MAE for the ground measurements with linear interpolation performing slightly better than stine interpolation in RMSE. Both methods exhibited varying bias across location and bin size for the ground measurement.

Our results indicate that some of the *simpler methods* such as stine and linear interpolation methods perform best compared to others for imputing NSRDB and ground measurements, respectively. Linear interpolation is the most appropriate choice of imputation method for the data in question due to its simplicity compared to stine interpolation. However, it is important to apply all methods when imputing new data sets to see which is most appropriate.
5. Acknowledgments

This work is supported in part by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The National Renewable Energy Laboratory is operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the Department of Energy or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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A Comparative Study Of Simulation Tools To Model The Solar Irradiation On Building Façades

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Abstract

This paper presents a comparison among eight tools commonly used to evaluate the solar irradiation in urban environments. The focus is on the vertical surfaces (i.e., façades). The analysed tools have a large range of applications, from detailed microclimate studies to large-scale irradiation modelling. The benchmark tests consist of simulations using two conceptual urban designs. Two representative winter and summer days are defined. The results, obtained for the modelling of the shortwave irradiance received on the façades, are discussed together with the observed differences. This work provides an overview of some of the available tools, their features, similarities, and differences as well as a comparison of the modelled solar irradiation. This work is conducted in the framework of IEA SHC Task 63 "Solar Neighborhood Planning" where experts from five countries, in six universities, two companies and one research institute have been engaged.

Keywords: comparative study, vertical façades, solar irradiation, numerical tools

1. Introduction

The use of solar energy in urban environment is considerably spreading IRENA (2019). In this context, it is crucial to model the solar irradiance in cities, which are characterized by complex built environments and related complex urban phenomena such as overshading effects and solar mutual inter-buildings and ground reflections. Indeed, the knowledge of the solar irradiance is important for passive and active uses of solar energy. In urban environment, photovoltaic (PV) systems installed on roofs represent most of the existing installed capacity. However, the integration of PV systems on façades becomes increasingly appealing due to a drop in PV technology prices and the large availability of vertical surfaces for energy production. Moreover, the production profile of PV components installed on façades is often shifted compared to roof-integrated PV modules, which allows for smoothening the electric production during the day Freitas and Brito (2019). An increasing number of simulation tools have now the ability to model solar irradiance in urban environments. However, it is crucial to understand how these tools work as well as what their main

© 2021. The Authors. Published by International Solar Energy Society Selection and/or peer review under responsibility of Scientific Committee doi:10.18086/swc.2021.38.04 Available at http://proceedings.ises.org features, level of accuracy, similarities, and differences are. To this end, this work presents a comparative study of results from ten simulation tools with a focus on the vertical façades.

2. Methodology

To compare results obtained with the selected tools, different levels of complexity will be analysed. Three scenarios have been considered. In the first scenario (i.e. Unshaded roof and Unshaded façade) we will consider the case of an unshaded building, while in the second scenario (i.e. Homogenous district) we will consider the case of a district with a regular distribution of same-size buildings and in the final scenario (i.e. Heterogeneous district) the case of a more random distribution of buildings with different heights.

2.1. Geometry

The homogeneous district presented in Figure 1 (a) is composed of three rows of three buildings. The buildings have identical heights and they are vertically and horizontally aligned. The heterogeneous district (b) is composed of non-aligned buildings with various heights. Each of these districts is composed of nine buildings with a footprint of $20 \times 20 m^2$. Each building is composed of N_f floors, with every floor being 3 m high. For example, a building with $N_f = 5$ will be 15 m high. For each district, the focus is on the central building, coloured in red in Figure 1.



Figure 1 Theoretical district geometries: (left) homogeneous district, (right) heterogeneous district. North is oriented upward.

Note that despite these two districts having distinct geometry, they have been designed to share similar common urban form indicators Natanian et al. (2019). These indicators are summarized in Table 1.

Table 1: Urban morphology indicators of the districts					
Indicator	Definition	Value			
Shape factor	Ratio between building envelope surface and building volume	0.23			
Floor area ratio	Ratio between building gross floor area and site area	2.5			
Site Coverage	Ratio between building footprint and site area	0.25			
Average Building Height	Average height of buildings in an urban model (m)	30			
	Albedo and reflection coefficients	0.2			

2.2. Weather data

For the weather inputs, data from the Meteonorm database corresponding to the location of Geneva, Switzerland

(latitude: 46.2044° N, longitude: 6.1432° E), has been used. This database provides hourly data weather conditions (e.g., irradiation, wind speed, temperature, and humidity). The analyses were conducted on two days, one in August and one in February, corresponding to typical summer and winter conditions. The investigated days are obtained from an average of the weather conditions for the considered month. For example for weather input *W* (e.g. direct irradiation, wind speed, temperature), the monthly averaged weather inputs are obtained by:

$$W_m(h) = \frac{1}{N_m} \sum_{k=1}^{N_m} W_k(h)$$
 (eq. 1)

where the subscript *m* corresponds to the considered month (here February or August), N_m corresponds to the number of days in the month and *h* is the hourly time step. Finally, the sun paths corresponding to the days of the 15th of February and the 16th of August will be considered as suggested by Klein (1977). The weather file contains the direct normal irradiance B_n , the horizontal sky diffuse irradiance D_h and the global horizontal irradiance G_h .

2.3. Temporal and spatial resolution

To conduct the comparative study, all tools must follow the same settings which include the geometry, the thermal properties (i.e. reflection coefficient), the weather and the temporal and spatial resolutions. Not all tools can achieve the same resolution, as some tools focus on district/city scale in which spatial and temporal resolutions are usually much coarser than in tools working at the room/building level.

For the spatial resolution, the surface of the selected building (i.e. central building) is divided into an analysis grid of 1 m^2 resolution. Results are collected at an hourly resolution. These spatial and temporal resolutions allow for all considered tools to achieve simulations within a reasonable computational time. Higher spatial resolutions would be necessary if superstructure elements were present Peronato et al. (2018), but for these simple geometries and flat surfaces, a 1-m^2 resolution is sufficient Govehovitch et al. (2021). Regarding the temporal resolution, most of the studies at the district scale consider yearly or monthly cumulated energy. Therefore, an hourly resolution is here sufficient for the aim of this study.

2.4. Output solar irradiance and insolation

As mentioned, results are collected at an hourly resolution. From here two solutions are possible:

- 1. The results are provided as an instantaneous snapshot at the required time, in this case it would correspond to a distribution of the radiative heat flux (in W/m²) on the surfaces of the selected building.
- 2. Provide an integration of the irradiance during a certain period, here an hour. In this case the result is an energy (in W.s/m², or in Wh/m² in the case of solar energy, 1 Wh being the integration of 1 W for one hour). This is sometimes referred to as the 'insolation' or 'irradiation'.

Depending on the adaptability of the tools, it is not always possible to select the required output as some tools impose the output results, either as an irradiance or as an hourly insolation. In what follows, results are presented in terms of irradiation. In the case the tool provides an irradiance, this irradiance is considered as constant for one hour, which leads to an hourly insolation/irradiation. Therefore, the results of this study will be provided in Wh/m².

2.5. Investigated tools

The investigated tools for the comparison study are listed in Table 2. The tools have been selected according to the individual experiences gained by the experts (i.e. co-authors) within the International Energy Agency – Solar Heating and Cooling programme Task 63 "Solar Neighborhood Planning" (Task 63).".

Tool Name	Code access	Radiation method	Simulation Engine	Diffuse model
Solar Cadastre of Geneva (CaS)	Closed	Radiosity	Own Engine	Hay
CitySim (CiS)	Open	Radiosity	SRA	Perez
De Luminae (DL)	Closed	Ray-tracing	Radiance	Perez
Diva For Rhino (Diva)	Closed	Ray-tracing	Daysim	Perez
ENVI-met (EM)	Closed	Radiosity	Own engine	Isotropic
Honeybee (HB)	Open	Ray-tracing	Radiance	Perez
htrdr-ModRadUrb (ht)	Open	Monte-Carlo (Ray-tracing)	htrdr-0.6.1	Isotropic
Indalux (Ind)	Open	Ray-tracing	Radiance	Perez
Ladybug (LB)	Open	Ray-tracing	Radiance	Perez
Spacemaker (SP)	Closed	Ray-tracing	Own Engine	Simple Sandia Sky

Table 2 List and features of the investigated tools in the comparison study

CadSol

The Solar cadastre of Geneva is a geographic information system (GIS) originally created at the Haute école du Paysage d'Ingénierie et d'Architecture de Genève (Hepia), and further developed though different project as it is now within the G2Solaire, INTERREG V project. This tool provides an estimate of the irradiation received on the roofs of the Greater Geneva agglomeration (2000 km²). A detailed presentation of the tool can be found in Desthieux et al. (2018).

• CitySim

CitySim was initially developed at EPFL (the Swiss Federal Institute of Technology in Lausanne) and the solver is currently maintained and further developed as an open-source tool at the Idiap Research Institute. A Graphical User Interface (CitySim Pro) is released as commercial software by Kaemco LLC. CitySim is a complete tool for dynamic urban energy simulation, including solar potential, building energy demand, district heating networks and outdoor comfort. For solar radiation, it includes the Simplified Radiosity Algorithm by Robinson and Stone (2005) and the Perez All-Weather model for the sky radiance distribution.

• DL-Ligth

DL-Light is the software suite developed by De Luminæ to help the evaluation of the intake and distribution of natural light in architectural and urban spaces. It is based on Radiance ([DL-LIGHT]).

• Diva

DIVA-for-Rhino is a highly optimised daylighting and energy modelling plug-in for Rhinoceros. This software uses ray-tracing and light-backwards algorithms based on the physical behaviour of light in a 3D volumetric model. For hourly solar radiation, the Daysim interface is used Reinhart and Walkenhorst (2001).

• ENVI-met

ENVI-met is a software aiming at simulating the urban microclimate by taking into consideration all the complex phenomena that occur in an urban environment. It is based on coupled balance equations (including those of mass, momentum, and energy). This involves taking the built and natural environment into account Simon et al. (2021).

• htrdr

htrdr-ModRadUrb is a numerical tool developed from the free and open-source software htrdr-0.6.1 ([htrdr].) that implements a Backward Monte-Carlo algorithm to compute longwave or shortwave radiative intensities in urban geometry by solving the monochromatic radiative transfer equation in the semi-transparent atmosphere with

Lambertian or specular surfaces. The htrdr-ModRadUrb tool used for this specific study includes a uniform and isotropic model of the sky for the computation of shortwave radiative fluxes as well as grey and Lambertian surfaces.

HoneyBee

Honeybee is an open-source plug-in part of the Ladybug Tools, working inside visual programming environments such as Grasshopper and Dynamo. It supports detailed daylight and solar irradiation simulations using Radiance and energy simulations using EnergyPlus and OpenStudio ([HB]). The study was performed using the improved two-phase Radiance method, available in the Honeybee [+] version of the plug-in.

Indalux

INDALUX is an open-source software package using RADIANCE as a calculation engine to produce particular images characterizing the urban fabric and sky radiance distributions. Various numerical indicators characterising the access to solar radiation (e.g. solar irradiation) and daylight in urban areas can be visually estimated or precisely calculated by overlaying these particular images. ([IDLX]).

Ladybug

Ladybug provides climate graphics based on weather files and supports solar radiation studies, view analyses, and sunlight-hours modelling. It is embedded within the visual programming language environment Grasshopper, linked to Rhino3D ([HB]).

• Spacemaker

Spacemaker's photovoltaic analysis is a prototype and is still under active development. However, it will be available to users in a Beta release in the Spacemaker product soon. The photovoltaic analysis uses local solar radiation data and Spacemaker's sun analysis to give users the ability to see the potential of their site for solar panel energy generation at the early phases of design ([Spacemaker]).

3. Results

To compare results obtained with the different tools, various levels of complexity will be analysed. First, we will consider the case of an unshaded building, then the case of a homogeneous district and finally the case of a more random distribution of buildings.

3.1. Unshaded roof

Unlike the geometry presented in Figure 1, the building considered in this section has no neighbours' buildings around it and, therefore, is not subject to any shadings or reflection from the surrounding built environment, except those from the ground. Hence, these results can be used as a reference to assess the impact of the surrounding geometry on the received solar irradiation. The hourly solar irradiation received on the flat roof in the case of an isolated building is presented for the day of February in Figure 2.



Figure 2 Hourly irradiation received on the roof in February

Here all the tools provide similar results. This is expected since in the present case the surface of interest is horizontal without any shadings or potential solar reflections. Therefore, the results should be almost identical to the G_h provided in the weather file. However, it can be observed that results are non-identical. This is mostly due to how each tool handles the input information. Indeed, based on the .epw data dictionary, ("EnergyPlus Weather File (EPW) Data Dictionary: Auxiliary Programs — EnergyPlus 8.3,"), the meteorological quantity provided at the hour *h* corresponds to the integral/average of this quantity over the previous hour. To account for this, some tools shift the sun position by approximately 30 min before the required hour. Consequently, for a result at hour *h*, the sun position at *h*-30min is sometimes used. However, unless we have total access to the source code, it is sometimes difficult to know whether this shift is done or not in the tool. Furthermore, this correction can be relevant with *epw files*, but it may not be relevant for other input files.

3.2. Unshaded facades

The irradiation on the North, West and South façades for the unshaded case is presented in Figure 3. Here it can be observed that the results on the North façades are relatively more sensitive with differences that can reach more than 100% at 1.00 p.m. However, this only represents an absolute difference of 60Wh/m². Given that there is no direct sun on this façade, the observed differences will mainly come from the diffuse model and the reflections. For example, for the present simulations, htrdr used intentionally an isotropic sky which results in a higher predicted irradiation on the North and a lower value on the southern façade. On the other hand, LB tool does not consider reflections, which results in a lower prediction of the solar irradiation. On the southern façades, differences by up to 150 Wh/m² are observed at 2.00 p.m., which corresponds here to a relative difference of 50%.



Figure 3: North, West and South façades fort the unshaded case in February

3.3. Homogeneous district

The spatially averaged hourly irradiation received on the southern façade for the homogeneous district has been plotted in Figure 4 for February (left) and August (right).



Figure 4: Irradiation on the southern face of the homogeneous district (left) February, (right) August

The impact of surrounding buildings can be seen in February since they generate a 'double hump' shape around 1.00 p.m. A maximum absolute difference of 100 Wh/m² is observed at 1.00 p.m. This represents a relative difference of 43% which is less than the maximum relative difference observed in the unshaded case.

3.4. Heterogeneous district

For the heterogeneous district (Figure 5) the predictions of the different tools are once again in good agreement. However, in winter, the solar irradiation is more sensitive to the district because of the lower position of the sun. Despite the relatively good agreement, the peaks (minimum or maximum values) are not predicted at the same time. For example, according to SP or Indalux the minimum during the day is reached at 10 a.m. whereas CaS or HB predict it the next hour. Similarly, the second peak is not predicted at the same time by all the tools. Finally, it can also be seen that in this more complex scenario, there is no tool that either provides maximum or minimum results for all timesteps compared to the other tools. For example, at 1.00 p.m., *SP* provides the maximum predicted irradiation, whereas at 2.00 p.m. and 3.00 p.m. it is respectively CaS and HB that predict the highest irradiation.



Figure 5 Irradiation on the southern face of the heterogeneous district (left) February, (right) August

3.5. Prediction variability

To better assess the variation of the results, we define here the variation of hourly irradiation I(h) of the k^{ith} tool by:

$$I'_{k}(h) = I_{k}(h) - \frac{1}{N_{T}} \sum_{n=1}^{N_{T}} I_{n}(h)$$
 (eq. 2)

 N_T being the number of investigated tools here $N_T = 10$.

The daily evolution of the distribution of $I'_k(h)$ is plotted in Figure 6 for the West façade for the four different scenarios (February, August, homogeneous/heterogeneous). Here the minimum and maximum values of $I'_k(h)$ (defined as min/max($I'_k(h), k \in N_T$) as well as the 25th and 75th percentile of $I'_k(h)$ are plotted. It can be observed that the difference between the maximum and minimum predicted value can be significant, up to 150 Wh/m². This represents the largest deviation observed in the results.



Figure 6: Evolution of the variation of $I'_k(h)$ during the day for the West façade in the four different scenarios.

To have a better overview of the variations in the irradiation for all tested configurations, we define a global indicator called the deviation intensity (DI). It is defined here as:

$$DI = \frac{\sum_{h=1}^{24} \sqrt{\sum_{n=1}^{N_t} I'_k(h)^2}}{\sum_{h=1}^{24} \sum_{n=1}^{N_t} I_k(h)},$$
 (eq. 3)

which can be seen as the daily average of the standard deviation divided by the daily average of the tool-averaged irradiation. This allows scaling the standard deviation by the mean daily irradiation which provides a better insight into the variability between the results (Table 3).

Table 3: DI values for the different periods and scenario

Period of analysis	February			August		
Scenario	unshaded	homo.	hetero.	unshaded	homo.	hetero.
East	17.4 %	14.0 %	37.0 %	17.5 %	14.5 %	33.0 %
West	14.1 %	12.9 %	49.0 %	13.5 %	18.1 %	38.7 %
North	17.6 %	26.0 %	46.4 %	24.3 %	36.0 %	45.5 %
Roof	3.4 %	3.4 %	8.3 %	3.0 %	3.0 %	8.4 %
South	14.2 %	10.7 %	16.8 %	13.8 %	7.9 %	10.0 %

For the day of February, it should be noted that, except for the North façade, the *DI* is lower for the homogeneous district than for the unshaded building. These results might seem slightly counter-intuitive since by increasing the complexity of the geometry, i.e., by adding buildings to the district, one would expect a higher diversity in the results. In August there are no special trends since, in the homogeneous district, the *DI* is higher for the North and West façade, whereas it is less for the South and East façade.

However, for both the investigated days, the *DI* is significantly higher in the heterogeneous district. This could be explained by two factors:

- The geometry is relatively random, without any symmetries, therefore increasing the complexity of the shadow castings.
- The analysed building (i.e. central building in the heterogeneous district, Figure 1) is small compared to its neighbours. As a result, it is highly shaded by the other buildings. In this case, the impact of the modelling of the reflection and the diffuse components are predominant.

3.6. Façade Mapping

One of the issues with the spatial averaging performed for previous figures is that it can erase or smooth some behaviours. To have a better idea of the difference between the tools, the distribution of the irradiation on the façade can be studied. This is illustrated in Figure 7 with the East façade of the homogeneous district in February. The three rows respectively correspond to 9.00 a.m., 10.00 a.m. and 11.00 a.m. As mentioned in sections 2.1 and 2.3, the façade is 30-m high and 20-m long, and the spatial resolution is 1 m^2 .



Figure 7: Distribution of the irradiation at 9.00, 10.00 et 11.00 a.m. (1st, 2nd and 3rd lines). Case of the East façade of the homogeneous district in February. The colour scale, ranges from 0 to 300 Wh/m², displays the hourly irradiation (in Wh/m²)

First, it can be observed that all tools provide a different distribution of irradiance. Nevertheless, some common features are visible:

• Some tools predict a sharp distribution of solar irradiance. It is here the case of Spacemaker, htrdr, HoneyBee, CadSol and ENVI-met. Indeed, for these tools, it is possible to visualize and localize which parts of the building envelope (façades and roof) are hit by the direct component at the evaluated hour.

However, even between these tools, differences in the shape occurs. This is due to a difference in the sun position. Indeed, depending on when within the hour the sun position is evaluated, the distribution of the direct radiation on the façade is impacted. This is particularly striking when comparing HB, htrdr and SP. Considering the results at 10.00 a.m., htrdr evaluates the sun position 30 min behind the required hour, therefore at 9.30 a.m. Based on that, the shape of the irradiance distributions, suggest that HB evaluates the sun position at a later time, here maybe at 10.00 a.m., whereas SP evaluates it an earlier time, maybe 9.00 a.m.

- A more continuous spatial distribution is observed in Indalux. The reason for this is that Indalux proceeds to a sub-hourly evaluation of the sun path at six intermediate positions within the hour. From this, six distributions of solar irradiances are calculated and averaged to provide the final hourly outcomes.
- It is interesting to observe that there are no significant differences in the distribution of the solar irradiation between tools using radiosity methods (e.g. Cadsol, CitySim, ENVI-met) from those using a ray-tracing approach (htrdr, HB, Diva). However, for all tools, reflections were diffuse. Introducing specular reflections (by adding glass walls for example), could have provided another outcome since classic radiosity approaches cannot account for the incidence angle (and therefore the specular reflections).

4. Conclusive remarks

This paper shows a critical comparison of the results obtained with some popular simulation tools for urban solar radiation studies. In total ten tools were studied for three scenarios, an isolated building (Unshaded), a building in an aligned district (Homogeneous), a building in a more random district (Heterogeneous). Each tool simulated the hourly solar irradiation on the envelope (façades and roof), for two representative days, one in August and the other in February.

• One of the striking points of this study is that, for similar input conditions and standard inputs, there are as many different results as tools. However, it should be noted that, despite using the same settings, the instructions sent to the contributors (and co-authors) did not specify an explicit sun position for each hour, which led to possible differences in dealing with the input parameters, notably due to the consideration of the hourly weather data as instantaneous or time-integrated values.

• There are very small variations between the tools outcomes when predicting the solar irradiation received on an unobstructed flat roof. However, predicted solar irradiation can largely vary for the façade, by up to 150 Wh/m² in the present case (40% in relative error).

• No single tool constantly over- or under-estimates hourly spatially-aggregated results with respect to the other tools. This would suggest in principle lower deviations if results were integrated over larger time scales.

• When comparing the relative difference of the mean solar irradiation there are no significant differences in the tools' results between the unshaded and the homogeneous scenarios. However, the deviation in the predicted irradiation significantly increases in the heterogeneous district. The reason is that the heterogeneous district is more complex, and the studied building in this scenario is smaller than its neighbours, and therefore subject to more shading.

• In some specific cases, explanations have been found to observed differences in the predicted solar irradiation (i.e. time at which the sun position is calculated, type of diffuse model, absence of reflection). However, some differences and behaviours remain unexplained, as this would require a more thorough analysis of the backend simulation engine/source code of each tool, which was out of the scope of this paper.

This work finally highlights that, depending on the tool and settings that are used, unneglectable deviations in the hourly results can be expected, especially for complex geometry.

5. Acknowledgements

The authors would like to thank the program INTERREG V Suisse- France for providing financial support to conduct this study in the framework of the project G2 Solar, which aims at extending the solar cadaster to the Greater Geneva area and increasing energy solar production at this level. This work has been supported by the HES-SO University of Applied Sciences and Arts Western Switzerland in the framework of the project VALES, as well as has by the French National Research Agency, through the Investments for Future Program (Ref. ANR-18-EURE-0016 - Solar Academy). The research units LOCIE is a member of the INES Solar Academy Research Centre. G.P. acknowledges funding from the European Union's Horizon 2020 research and innovation program under grant agreement N°884161. Thanks to the IEA SHC Task 63 'Solar Neighborhood Planning' that provided the framework to gather the expertise required to achieve such work.

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Design and focusing performance simulation of trough solar concentrator

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Abstract

Abstract: In order to minimize the focal plane spot size of trough solar concentrator with fixed opening width, the bus equation of trough solar concentrator is calculated theoretically. According to the Monte Carlo ray tracing method and the law of mirror reflection, the focusing performance of a trough solar concentrator with an opening width of 5.77 m and a length of 0.4 m is simulated. The error between theoretical analysis and simulation results is 2.6% in terms of received energy on focal plane. This will provide a reliable basis for the design and optimization of trough concentrating system.

Keywords: Trough solar condenser, Focusing performance, Simulation

1. Introduction

Trough solar thermal power generation technology is the most mature solar thermal power generation technology at present (Wang, 2006). Therefore, based on the analysis of solar focusing theory, the focusing performance of a trough solar concentrator with an opening width of 5.77 m and a length of 0.4 m is simulated. It provides a reliable basis for the design and optimization of trough concentrating system.

2. Solar focusing analysis theory

In the analysis of solar focusing, 0.533 degrees misalignment of sunlight needs to be considered in the solar concentrating analysis (Xu et al. 2013), and following assumptions are made:

1) In the solar angle, the incident sunlight is considered to have the same irradiance in all directions;

2) Only the mirror reflection of paraboloid is considered;

3) The local sunshine constant is 1000 W m⁻² (Tao et al. 2011).

After the sunlight is reflected by the parabolic reflector, an optical path is formed on the xoy plane, as shown in Fig. 1. In the figure, "o" is the origin of the coordinate, "F" is the focus of the paraboloid, and "A" and "B" are the endpoints of the projection of the paraboloid on the xoy plane.



Fig.1: Optical path diagram of concentrator

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3. Design example and result analysis of trough solar concentrator

3.1 Design requirements:

1) The trough type solar concentrator is adopted, and its opening width is 5.77 m;

2) The focal plane spot size is the smallest;

3) The bus equation of trough solar concentrator is determined.

3.2 Calculation process of bus equation

Focal plane spot size CD can be calculated by:

$$cD = \frac{2 \times AF \times tan\frac{\theta}{2}}{cos\phi} = \frac{4 \times f \times tan\frac{\theta}{2}}{cos\phi \times (1 + cos\phi)} = \frac{2 \times AE \times tan\frac{\theta}{2}}{sin\phi \times cos\phi} = \frac{2 \times AB \times tan\frac{\theta}{2}}{sin2\phi} \quad (eq. 1)$$

Where, AB is the opening width of trough type solar concentrator, CD is the focal plane spot size, θ is the splitting angle of incident solar rays, ϕ is the angle between the normal incident light and the main optical axis.

When ϕ is 45 degrees, the minimum CD is 0.054 m

That is,
$$AF = \frac{AB}{2 \times sin \emptyset} = 4.08$$
 (eq. 2)
Then, $f = \frac{AB \times (1 + cos \emptyset)}{4 \times sin \emptyset} = 3.4825$ (eq. 3)

So, the bus parabolic equation is $x^2 = 13.93y$.

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3.3 Focusing performance simulation

A solar concentrator with bus parabolic equation is $x^2 = 13.93y$, opening width and length is 5.77 m and 0.4 m respectively, is established. The solar sunshine constant is 1000 W m⁻² and the lens reflectivity is 0.92. According to Monte Carlo ray tracing method and mirror reflection law introduced in literature, the energy flow distribution and energy size on the focal surface of the condenser are calculated Simulation. The sunlight perpendicular to the opening surface of the trough condenser is reflected by the condenser, and the energy is gathered on the focal surface and a spot is formed. The light path is shown in Fig. 2. The calculation results of the shape of the spot and the distribution of energy flow on the focal surface are shown in Fig. 3.



Fig. 2: Light path diagram



Fig. 3: distribution and size of energy flow in focal plane

As can be seen from Fig. 3, due to the existence of Fig. 2 light path diagram of the solar angle, the solar rays on the focal plane do not converge into a line, but form a rectangular region, with the peak energy of 1.5×10^5 W m². The total energy received by the focal plane is 21233.6 W. When the aperture area of the trough condenser is $5.77 \times 0.4 = 23.08$ m², the total incident energy is 23080 W. Therefore, the focusing efficiency of the trough condenser is 21233.6/23080 = 0.974, and the error between the theoretical analysis and the simulation results is 2.6%.

On the other hand, the focusing energy is mainly concentrated in the range of ± 0.03 m on the focal plane, which is basically consistent with the theoretical calculation width of 0.054 m focal spot. This is mainly because the theoretically calculated focal spot width CD consists of CF and FD segments. In the theoretical calculation, it is assumed that CF and FD segments are equal, but in fact FD segment is slightly longer than CF segment, so the actual focal spot width should be slightly longer than CD.

4. Conclusion

4.1 When the opening width is fixed, in order to minimize the focal plane spot size, a reasonable trough solar reflector is designed. According to the Monte Carlo ray tracing method and the mirror reflection law, the focusing performance of a trough solar concentrator with an opening width of 5.77 m and a length of 0.4 m is simulated;

4.2 Due to the existence of the solar angle, the solar light does not converge into a line on the focal plane, but forms a rectangular region. The peak energy is in the center of the rectangular region, decreases outward along

the length of the trough condenser, and is basically constant in the width direction of the trough condenser. The error between theoretical analysis and simulation results is 2.6% in terms of received energy on focal plane.

5. Acknowledgments

The research was supported by "Zibo science and technology development plan project (2017kj010054)" and "Zibo school city integration project (2020SNPT0064)".

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L-03. Solar Resource Measurements and Instrumentation

Method for flagging shaded solar data using a semi-graphical representation

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Abstract

Solar radiation monitoring instruments should have unobstructed views to the sun at all times of the day and the year as it moves across the local sky, and measured data should be quality-flagged automatically, as large amounts of data are to be processed. If shading is identified, the data at the shaded areas should be properly flagged and excluded from the 'usable' data; for this, the shaded areas have to be expressed in the data processing code as equations or conditions that define the areas and allow to determine whether any measurement was taken inside the shaded area. There is no established method for identifying and flagging those shaded data when analysing solar radiation measurements. This work presents a method that uses CERN's ROOT Data Analysis Framework to define the shaded area graphically in an efficient and precise way, translating this into a region against which each measurement is then easily checked in the code, and discarded or flagged accordingly.

Keywords: solar resource assessment, data quality, sensor shading

1. Introduction

When measuring solar radiation, the radiometers should have unobstructed views of the sun through the day from sunrise to sunset, throughout the full year. Sometimes, nevertheless, the site conditions are not ideal, and surrounding structures (buildings, trees, etc.) can obscure the sun from the line of view of the radiometers for varying periods of the day along the year. Even if at the time of installation there were no such obstructions, they can appear at later times and be either temporary or permanent. In any case, these obstructions result in incorrect measurements affecting all solar radiation components (Gb, G and Gd, i.e. the direct, global horizontal and diffuse horizontal irradiances, respectively).

To analyse data sets of solar radiation measurements, quality tests following international standards can be applied in order to identify erroneous values in the data and to flag them for their quality; however, the shaded data are not identified by these tests, since a shade cast by a cloud may have the same effect on the measurements as any other shade caused by an unwanted obstruction: Gb is reduced (as much as down to zero, depending on the size and opacity of the cloud or object) while Gd increases correspondingly, and G decreases to a lesser degree. While the data under clouds are realistic measurements, the shaded data resulting from an obstruction on the sensor do not represent the real site conditions and should be removed from the analysis or application.

One useful tool to identify shading issues is the azimuth-elevation (A-E) plot, which presents the irradiance values in a hemispheric sky view (Figure 1). In these graphs, similar to sun charts (Duffie and Beckman, 2013), the measured irradiances are plotted at all daytime moments through the year as function of the solar position in the local sky, covering up to 360° of azimuth in the x-axis, and 0 to 90° of elevation in y. For the northern hemisphere, each day's measurements trace an arc starting on the eastern side at the horizon, rising as the sun moves to the south direction at solar noon and again falling to the horizon towards sunset, but now on the western side; these daily paths are lower and narrower towards winter, and higher and wider towards summer. Since the extremes of the sun path are the summer and winter solstices, the year can be divided at those points so that the data points do not overlap on the plot; this results in two charts, one for each half of the year. Having these 2 charts per year also helps in the observation of persistent patterns of lower irradiance.

Direct normal irradiance, Gb, is much more sensitive to obstructions than the global or diffuse radiations, so in an A-E plot of Gb the obstructions can be more easily identified by eye as large dips in irradiance resembling the

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shape of the obstructing object. Irradiance can also decrease due to atmospheric conditions (mainly clouds or heavy aerosol/dust events), but a human can recognise obstructing patterns, especially with some training and experience. For instance, a cloudy day appears as an arc of lower irradiances, and random clouds appear as also randomly distributed dips, whereas a static obstruction will appear for localised times of the day but spanning through a number of days, potentially weeks or months.



Figure 1: Example of azimuth-elevation graph; the colour scale represents irradiances, in this case G in W/m². North is 0 (and 360) degrees in azimuth, while east, south and west are 90, 180 and 270 degrees, respectively.

Once undesired shaded areas have been visually identified, the problem remains of dealing automatically and efficiently with the measurements within those areas, that is, the processing code must determine whether a measurement was taken under the shaded conditions, to quality-flag and filter the data as needed. These shaded areas can be expressed as conditions and/or equations that identify data within them, and these conditions can be expressed as their corresponding solar zenith and azimuth region/s, or as timestamps, in the programming language used for the analysis (C++, MATLAB, Python,...). For the simplest geometries, such as squares or rectangles having their sides parallel to the horizontal and vertical, these conditions can be introduced easily in the code, for instance as a number of "if-then" expressions; however, more complex shapes (often the case of real obstructions) quickly become quite cumbersome to describe; even a rotated square is not simple to describe anymore due to the changing positions in both altitude and azimuth.

In this work, the ROOT data analysis framework (Brun and Rademakers, 1997), developed at CERN and based on C++ (but also integrated with Python and R), is used to facilitate the process of introducing the shaded areas into the data processing and quality-flagging code. Taking a dvantage of ROOT's general capabilities, the area is identified through a graphical definition, which is then easily integrated into the programming code to flag data inside this area.

2. Methodology

The ROOT framework contains many libraries and methods to analyse and manipulate data, to produce plots, do simulations, and many more tasks. It should be mentioned that ROOT has not been developed for solar resource applications; in fact, it was initially used for high-energy particle physics, but has enough flexibility for many other uses. Similarly to Matlab, for example, code for ROOT can be typed directly on an interactive prompt or saved in so-called 'macros' (e.g. C++ or Python files that use ROOT libraries) that can be executed from the interactive prompt, or in batch mode, or even compiled to executable files.

The key ROOT functionalities for the application in this work are:

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- Plots can be displayed in an interactive window called a 'canvas', on which the user can add different elements such as more plots, text, shapes, etc. Then, the elements present in a canvas can be saved as code, so that it can be reproduced by running this code (note that this is independent of any code that may have been used to create that canvas and its elements); this code is automatically generated by ROOT when the user chooses to save the canvas as a macro file.
- On a canvas, the user can draw areas in the form of open or closed polygons, that can be used as 'graphical cuts' and saved as code (basically, as x-y pairs that define the polygon corners) with the canvas.
- The function IsInside(), part of the "TMath" library (TMath, 2021), checks whether a given point (x,y) is inside or outside of a defined polygon.

With these tools, the strategy to introduce the shaded areas to the processing code is straightforward:

- Produce an interactive canvas with an A-E plot for a given irradiance (G, Gb or Gd).
- Visually identify the obstruction a rea/s and use the "Graphical Cut" tool in ROOT to define an area enclosing the shaded data that should be flagged.
- Save the canvas as .C file and find in it the graphical cut code, through which the cut is created.
- Add the graphical cut code into the macro that does the quality checks on the data. The azimuth and elevation angles of each irradiance data point are passed to the IsInside method of the graphical cut; if the point is inside, flag the entry as 'bad'.

Note that, naturally, in addition to the measured data (G, Gb, Gd), the azimuth and elevation (or the zenith, its complementary) angles of the sun at the corresponding site and time of each measurement must also be a vailable in order to produce the A-E plot, independently of the tool used to make this plot. There are a number of online calculators, with different precisions, from which the solar position can be obtained, and source code is also freely available so users can implement it in their own system; for instance, NOAA compiled a set of simple equations (NOAA, 2017), and NREL has the SOLPOS 2.0 and SPA algorithms (NREL, 2021).

The source code of the IsInside function in ROOT, as all ROOT code, is a vailable online by following the link on the IsInside method description in the TMath library documentation (c.f. above). In essence, the function consists of just one 'for' loop and two nested 'if' conditions; in a simplified way, the strategy is to count how many times a horizontal line passing through the tested point intersects the sides of the polygon to either the right or the left (both give the same result) of the test point. If the final number of crossings on either side is odd, the point is inside the polygon, and outside otherwise. The implementation in ROOT does this by going through each pair of corners, first checking whether the y coordinate of the test point is within the y coordinates of the two corners and if so, and to determine on which side the test point is, the slope between the test point and one corner is compared to the slope of the line of the two corners. Details and graphic examples of this method and other strategies to address the same problem can be found in the literature and online, e.g. in Finley (2007), Bourke (1997), Shimrat (1962), Hormann and Agathos (2001), Wiler (1994), Galetzka and Glauner (2017).

3. Results

Figures 2(a) and 2(b) show A-E plots covering five months of 1-minute measurements of Gb and G, respectively, from a station that has a high tower nearby (photo insert), at an azimuth of about 120° (30° south of east) and up to an elevation of around 35° . Note that for this location, at latitude 25° N, the sun reaches a maximum elevation of around 88° near the summer solstice, but the available data were only from December to April, which is, however, enough to include the full area of the sun paths obstructed by the tower.



Figure 2: A-E plots of Gb and G, (a) and (b) respectively, from December to April, for a site in which a nearby tower (photo insert) blocks the sensors' line of view to the sun for part of the morning during some months of the year.

The shading from this tower can be seen on the A-E plot of G; however, it is better identified on Gb, so this graph is used to define the graphical cut, first by zooming in on both x and y axes, then selecting the graphical cut tool and clicking on the all points (nine in this case) that define the corners of the resulting red polygon. Figure 3 shows the location of the Graphical Tool on a ROOT canvas Toolbar. Each point is added with a single mouse click (the last one requires a double-click), from which ROOT creates lines to define the polygon sides.



Figure 3: The graphical cut tool (indicated with the red arrow) on a canvas. Select the tool and click on each point of the canvas defining a corner of the polygon. The line colour, thickness and style can be changed on the Editor sidebar.

With the polygon created, the canvas can be saved as a ROOT Macro (*.C) file, from which the lines describing the polygon, which start with the definition of a TCutG object, can be retrieved. Figure 4 shows a sample ROOT macro that includes, in lines 2-17, the definition of the graphical cut representing the polygon of Figure 3. Excluding the lines within the 'if IsInside' condition (line 26), this could be a very simple but complete macro with all the user code needed to separate data inside a shaded area; moreover, note that lines 6, 16 and 17, for example, are not needed for this use, but were kept for completeness.



Figure 4: Code corresponding to the polygon in Figure 3 (lines 1 to 16), and testing each measurement to see whether they were taken inside the azimuth-elevation area defined by that polygon.

Note that the coordinates of the TCutG points can easily be edited by the user, for example to ensure perfectly vertical or horizontal lines if desired (as was done in the example shown here). Lines 18 to 24 in the same figure 4 show how the IsInside method is used to check and flag the azimuth-elevation coordinate pairs: as each irradiance and corresponding solar angles are being read, the solar angles are passed to the IsInside method of the TCutG object, which returns a boolean value of True if the pair (azimuth-elevation) is inside the polygon, and False otherwise. If the point is inside, the corresponding measured irradiances should be directly discarded (if they were going to be used at this point), or flagged as erroneous (if additional processing is to be done).

4. Conclusions

Measuring solar resources requires that, ideally, the radiometers have unobstructed views of the full sky hemisphere. This is not always possible, and some elements in the surroundings may directly block the sun from the line of view of the instruments for parts of the day for varying numbers of days, weeks or months. Given that automatic quality checks are not able to identify these conditions, users must first identify the problem areas and incorporate these in the code before processing the measured solar irradiances, in order to appropriately quality-flag and exclude the affected data. This work presents a method based on the existing capabilities of the ROOT data analysis framework, to easily define through a graphical interface the shaded areas and incorporate them in the processing code, to easily flag measurements taken when the sun was inside that area.

Although the procedure shown here is specific to ROOT, a user of other data analysis tools can translate the methodology used here to their own data analysis framework. For example, the points of the polygon could be defined 'by hand' and stored in vectors or arrays, and then a similar IsInside method can be implemented in any language, as the code is openly accessible. However, and as mentioned previously, ROOT already provides the IsInside method, and has the additional advantage of allowing to define the polygon in an interactive, graphical way, by simply clicking on the plot, an advantage that quickly becomes more convenient when the shaded area is not a simple geometrical shape.

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Surface azimuth estimation from solar irradiance on tilted surfaces

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Abstract

Azimuth misalignment of receiver surfaces is a frequent source of uncertainty when working with solar irradiance measurements on tilted surfaces (GTI). Two complementary methods to estimate the true azimuth of a tilted surface from GTI data are implemented and evaluated; the first method being a new one, and the second a variation of a previously existing one. Ground data from an arrangement of tilted pyranometers with different azimuths, along with global horizontal, direct normal and diffuse horizontal irradiance (GHI, DNI and DHI) data, are used to validate the methods. The results show good agreement with nominal azimuth values, with typical uncertainties of a few degrees that increase with the nominal azimuth. Both methods are complementary since they have different strengths and weaknesses.

Keywords: global solar irradiance, azimuth misalignment, tilted surfaces

1. Introduction

Non-concentrating tilted surfaces for solar energy collection maximize the received energy when oriented towards the equator (zero azimuth). Interpretation of measurements of solar irradiance on these tilted surfaces (GTI) relies on the accurate orientation of the surfaces. For several reasons, the actual surface azimuth (angle between the normal to the surface and the local meridian) may differ from its nominal value, and GTI data is misinterpreted. When measurements of global irradiance on the tilted surfaces are not available, radiation transposition models can be used to estimate GTI on arbitrary oriented surface orientation for optimal performance. Surface azimuth measurements are usually made with common GPS devices, with magnetic compasses or by using the shadow of a vertical rod at solar noon. In practice, these methods can be inaccurate by several degrees. Furthermore, GTI pyranometers mounted on remote measuring sites are exposed to extreme weather conditions which can result in azimuth misalignments of the tilted surface, which in a long time series might vary over time. These azimuth-related errors can have a direct impact on the energy output estimates and affect the economic analysis of solar energy systems.

Recently, this problem was addressed in Barbier et al., 2019 by proposing a method for estimating the misalignment of tilted surfaces by minimizing the error of a transposition model for estimating GTI at different azimuths. The estimates for GTI are derived from clear-sky estimates of GHI and its diffuse component (DHI) obtained from the McClear model

(Lefèvre et al., 2013), available at the Copernicus Atmosphere Monitoring Service (CAMS). To the best of our knowledge, we have found no other work on this topic.

In this paper, a new method (referred as Method PA) is described which can estimate the azimuth using only GTI data, and provides an estimate for its uncertainty. For a long time series this method is also capable of detecting changes in azimuth over time. A second method (referred here as Method BBSD) is also implemented and evaluated; it is a variant of that proposed in Barbier et al., 2019, based on the ESRA clear-sky model (Rigollier et al., 2000) and using ground data instead of satellite estimates. Controlled-quality laboratory data from two sites with eight tilted surfaces of well-known tilt and azimuth angles are used to evaluate both methods.

2. Data

The main source of GTI data comes from an array of pyranometers mounted on a specially designed semi-hemispheric structure at the PIMENT Laboratory (Reunion Islands, France). This one-year dataset includes 1-min resolution GTI data for several tilt and azimuth angles and was originally used for the evaluation of transposition models (David et al., 2013). Aside from the GTI data, five months of simultaneous GHI, DHI and direct normal irradiance (DNI) data are also included. The location, period and angles for this dataset are listed in Table 1. Other details on this measurement campaign can be found in (David et al., 2013). Additionally, data from the Solar Energy Laboratory (LES http://les.edu.uy, last access: 20/09/2021) in Salto, Uruguay, comprising two series of measurements of GTI corresponding to two tilt angles and zero azimuth are considered. This dataset spans five years (2016-2020) of 1-minute resolution simultaneous GHI, DHI and DNI data. The location and other details for both sites are listed in Table 1.

Site	Lat (°)	Lon (°)	Alt (m)	Label	Period	(Tilt, Azimuth) (°)
Reunion Island	-21.33	-55.50	76	PIM	11/2008- 12/2009	(20,0);(20,-30); $(40,0);(40,\pm30);(40,\pm60)$
Salto, Uruguay	-31.28	-57.91	56	LES	01/2016- 12/2020	(30,0);(45,0)

 Tab. 1: Location, labeling and orientation of the different datasets evaluated in this work. For the Southern Hemisphere, surface azimuth is zero for north-oriented surfaces, negative for surfaces facing North-East, and positive towards North-West.

GTI, GHI and DHI data for both sites are mostly from class A (spectrally flat) Kipp & Zonen pyranometers. The exception is that at the LES site GTI was measured using CMP6 pyranometers (class B, spectrally flat), see Table 2. The GHI and DHI instruments were ventilated and DNI was measured with Kipp & Zonen CHP1 pyrheliometers mounted on SOLYS2 solar trackers at both sites. The trackers where equipped with a shading ball that blocks the beam irradiance on the DHI pyranometers. These instruments received maintenance on a daily basis.

Details on the labeling and orientation of the different surfaces considered are shown in Table 2, where the number of clear days selected for Method PA of azimuth detection are also included.

Label	Tilt and Azimuth	Sensor model	Site	Clear days selected (method PA)
G40_60E	(40°,-60°)	CMP11	PIMENT	20
G40_30E	(40°,-30°)	CMP11	PIMENT	35
G20_30E	(20°,-30°)	CMP11	PIMENT	33
G45_0	(45°,0°)	CMP6	LES	26
G40_0	(40°,0°)	CMP11	PIMENT	28
G30_0	(30°,0°)	CMP6	LES	35
G20_0	(20°,0°)	CMP11	PIMENT	24
G40_60W	(40°,60°)	CM11	PIMENT	21
G40_30W	(40°,30°)	CMP11	PIMENT	26

Tab. 2: Location, labeling and orientation of the different datasets evaluated in this work. For the Southern Hemisphere, surface
azimuth is zero for north-oriented surfaces, negative for surfaces facing North-East, and positive towards North-West.

3. Methods for surface azimuth estimation

3.1. Method PA

For sun-facing tilted surfaces, GTI data under clear sky conditions as a function of the hour angle ω have well defined daily maximums. Let ω^* be the hour angle that maximizes GTI; if is zero, the surface is oriented towards the equator and its azimuth equals zero (if the proper azimuth convention for each hemisphere is used, a zero azimuth corresponds to a surface oriented towards the equator in both hemispheres). For an observer in the southern hemisphere, if ω^* is negative the surface is facing North-East and maximum GTI occurs before solar noon; if ω^* is positive the surface is facing North-West and maximum GTI occurs after solar noon, as shown in Fig. 1. Thus, ω^* has the relevant information about the true surface azimuth.

If simultaneous GHI data are available, automatic clear sky detection algorithms may be used to find days with clear intervals containing the GTI maximum ω^* . Otherwise, a careful visual inspection of the data is required to select the clear days for which the GTI maximum is well defined. Fig. 1 shows an example of clear sky GTI data for three surface orientations from the PIMENT dataset, together with GHI data.

A three-step procedure is followed to find the true azimuth: (i) first the suitable days from the GTI time series are selected, and an auxiliary function $\gamma = f(\omega^*)$ that relates the surface azimuth with the hour angle that maximizes GTI is determined for each of them. (ii) the hour angle ω^* for which GTI has a maximum is determined, together with its corresponding azimuth candidate $\gamma = f(\omega^*)$. Finally, (iii) the final surface azimuth γ is determined by averaging the azimuths candidates for all days and its uncertainty is also characterized using

the standard deviation.



Fig. 1: GTI data for different surface orientations from the PIMENT dataset, corresponding to a clear day in March 2009.

3.1.1. Clear day selection and parametrization of the auxiliary function $\gamma = f(\omega^*)$

Starting with high resolution (1-minute or smaller intervals) GTI data, days with clear-sky conditions around the GTI maximum are selected. This step must be performed manually unless a set of reliable, simultaneous GHI data is available. In this case, automatic detection algorithms for clear sky conditions can be used. Otherwise, careful visual inspection of the GTI data is required.

For each selected clear day, the function $\gamma = f(\omega^*)$ that relates the hour angle that maximizes GTI with the surface azimuth, is parametrized. This function depends on the site and also (weakly) on the day number (n=1,2,... 365) and so it must be determined for each selected day in the GTI series.

The parametrization of this function relies on a clear sky model and proceeds as follows. For each selected day, horizontal clear-sky estimates for GHI, DHI and DNI are generated. We use the ESRA clear-sky model (Rigollier et al, 2000) for this task due to its simplicity and the fact that it requires only one parameter (the Linke turbidity, T_L). For a range of surface azimuths, which must include the "true" azimuth, the Perez transposition model (Perez et al, 1993) is applied to estimate the corresponding clear-sky GTI values. We favor this refined transposition model instead of other simpler models, for technical reasons which are clarified below. The ground is assumed to be a perfect diffuse isotropic reflector with a fixed surface reflectance of 0.25.

Locally adjusted daily T_L cycles for the Uruguayan region, calculated in (Laguarda and Abal, 2016), were used for the LES site. Linke turbidity data from the Reunion Island were obtained from the PVLIB Python library (Holmgren et al., 2018), which is based on generic global estimates (Remund et al. 2003).

As can be seen in Fig. 2 (left panel), the GTI estimates obtained using the ESRA clear-sky estimates and the simple isotropic transposition model (Liu and Jordan, 1961) show significant variations in the solar times of their maxima for different values of T_L . The right panel of Fig. 2, uses the same ESRA clear sky estimates but with the Perez transposition model, which results in a weaker dependence on T_L and is therefore more suitable for this



procedure than the simple isotropic model.

Fig. 2: Comparison between calculated GTI from GHI/DHI/DNI ESRA clear sky estimates with different Linke turbidity values, for a 30° tilt / 30° azimuth surface. Left: GTI from the isotropic transposition model. Right: GTI from the Perez model.

To parametrize the function $\gamma = f(\omega^*)$ we propose a fitting of the form $\gamma = a \times \tan(b\omega^*)$, where the angles γ and ω^* are in radians. The coefficients (a, b) are obtained using least squares optimization and, as mentioned before, have a weak seasonal dependence on the day of the year. If the nominal value of the surface azimuth is known, the fitting can be improved by performing it in a small neighbourhood of this nominal value.

Two examples of this procedure are shown in Fig. 3, for $+30^{\circ}$ and -60° azimuth angles. An indicator of the goodness of fit, coefficient R² defined as R² = 1-(SSres/SStot) where SSres is the sum of squares of the residuals and SStot is the total sum of squares, was calculated for each day selected. It ranged from 0.9995 to 0.9997, which ensures that the fitting is accurate. It can be seen that the absolute slope of the function increases with the absolute surface azimuth, which means that small variations in ω^* imply large variations in the estimated azimuth (hence amplifying the uncertainty of the method for large angles). This slope is almost vertical for azimuths close to 90°, which makes this method unsuitable for extreme deviations from $\gamma=0$. This is not a strong limitation, since energy absorbing surfaces are usually oriented towards the equator.



Fig. 3: Two examples of the fitting and evaluation of the $f(\omega^*)$ function, for different orientations. Coefficients of the proposed fitting are given for those particular days, as well as the R² coefficient. Results show good agreement with the surface azimuth nominal values. The range of azimuths used for the fitting is between -90° and +90°.

3.1.2 Estimation of ω^*

Once the suitable days with clear-sky conditions around the GTI maxima have been selected and the parameters (a, b) have been determined, the hour angle ω^* for which the maximum is attained must be found. For each of these days, a suitable interval centered around the solar time when GTI is maximum is selected. As can be seen from Fig. 4, at the 1-minute timescale, raw data can have small ripples or noise which may affect the determination of the solar time for the maxima. In order to smooth out these irregularities, a quadratic polynomial of the form $\gamma = a_2\omega^2 + a_1\omega + a_0$ is fitted to the data in this interval. Outliers are rejected by an iterative procedure in which data points that differ from the fitting curve by more than a certain tolerance value are labeled as outliers and discarded. New polynomial is fitted to the remaining data and the procedure is repeated until all the data satisfies the criteria. In actual practice, it converges after a few iterations. Finally, the hour angle that maximizes the fitting curve, $\omega = -a_1/2a_2$, is the best estimate for ω^* on the given day.

3.1.3 Estimation of the surface azimuth over time

By substitution of ω^* into the corresponding function $\gamma = a \times tan(b.\omega^*)$, the azimuth estimate γ_i for clear day i is obtained. Fig. 3 shows two examples of such substitution. Repeating this process for each clear day in the GTI series with clear skies at maximum GTI, a series of azimuth estimates results. If no drastic changes of azimuth are identified over time, the simple average of this series is the final estimate of the surface azimuth, γ , and the standard deviation provides an estimate of the accuracy *u* of the method.



Fig. 4: Examples of GTI 1-minute data as a function of the hour angle (in degrees) near their maxima, for two different orientations. Left: 40° tilt and -30° azimuth; right: 20° tilt and 30° azimuth. Data are fitted in order to obtain ω*, which will be used to estimate the azimuth.

3.2. Method BBSD

As mentioned, this method was first proposed in (Barbier et al., 2019) using both surface orientation angles, and satellite-based clear sky estimates for the horizontal irradiance components. It is based on the comparison between measured and estimated GTI from a suitable transposition model. Ideally, it requires simultaneous GHI, DHI and DNI data at 1-hour or subhour time scales. The clear-sky estimated and measured GTI values are compared for several azimuth values around the nominal or expected azimuth, and the azimuth that minimizes the deviations is selected.

For this paper, this procedure has been implemented using a 1-minute dataset with simultaneous (GHI, DHI, DNI, GTI) measurements and it can be described in four steps, as follows:

(i) The data was filtered according to the quality control criteria proposed in (Perez-Astudillo et al, 2018), which include the relevant Baseline Solar Radiation Network (BSRN) tests. In particular, data corresponding to solar altitudes less than 10° were rejected in order to reduce the impact of cosine errors. Other reasonable quality control filtering procedures can be followed for this initial stage.

(ii) An automated clear-sky detection algorithm (Reno and Hansen, 2016) was used to identify clear sky data by comparison of measured GHI and the clear-sky estimates from the ESRA model. Clear sky filtered data thus selected were averaged into 10-minute intervals, since this method does not require high time-resolution data. An averaged interval is computed only if 2/3 of the data that comprise it passed the filters and the clear sky detection; otherwise it is labeled as NaN.

(iii) GTI is estimated from GHI, DHI and DNI data for a range of surface azimuths, which must include the nominal value. We refer to these estimates as $GTI_e(\gamma)$. The anisotropic Perez transposition model is used for this purpose, since it is one of the best transposition models and better describes the anisotropic characteristics of the cloudless sky (D. Yang, 2016).

(iv) The modeled $GTI_e(\gamma)$ are compared with the measured GTI using the Relative Root Mean Square Deviation (rRMSD), expressed in relative terms (%) with respect to the mean of the measurements \overline{GTI} :

$$\mathrm{rRMSD} = \frac{100}{\overline{GTI}} \times \sqrt{\frac{1}{N} \sum_{i=1}^{N} (GTI_{e,i} - GTI_{m,i})^2}$$
 (eq. 1)

where N is the number of samples, $GTI_{e,i}$ are the estimated values and $GTI_{m,i}$ are the measured GTI values. The azimuth that minimizes the rRMSD is our first estimate of the true surface azimuth.

A standard random sampling and cross validation procedure is performed (one thousand iterations with 50/50 split of the data set for training and evaluation subsets) and the average azimuth γ is the best estimate from this method. Its standard deviation is a measure of the statistical uncertainty (variability within the ensemble) associated with this method and it is usually negligible compared with the total uncertainty.

Conceptually, this method is simpler than the method PA described in Section 3.1, which has the advantage of requiring only GTI measurements for the site. However, under PA, the measurements must have high time resolution (1-minute intervals) and must include several clear sky periods with well defined GTI maximums.

3.2.1. Data filtering

For this method, good quality ancillary data (GHI and DHI or DNI) must be available in order to avoid selecting clear samples which contain traces of clouds, since this can affect the accuracy of the azimuth determination.

For the PIM experiment, 78669 simultaneous diurnal 1-minute samples of the three components (GHI, DHI, DNI) and GTI for several orientations were jointly available for a period of six months between February and July of 2009. For the LES site, 1434844 diurnal 1-minute records are available for a five year (2016-2020) containing the three components (GHI, DHI, DNI) and GTI for two tilt angles and zero azimuth (see Tables 1 and 2).

The same set of filters (F1 to F18 proposed in Pérez-Astudillo et al. 2018) are applied independently to the (GHI, DHI, DNI) components in both datasets. These filters include the relevant BSRN filters (Long and Shi, 2006) and are complemented with filters to detect other conditions, such as misalignment of the tracker. Modified parameters are used as needed. The last filter, F19, is a visual inspection mask which removes a few (less than 0.1% of the samples) data artifacts and astronomical events (such as eclipses) from the datasets.



Fig. 5: Diffuse fraction vs clearness index diagram for the PIM site. Data discarded by the filtering process is greyed out and the selected clear samples are highlighted in red.

After the filtering process and clear-sky data selection, 26142 clear samples were selected for the PIM site (all orientations). For the LES data, after integration to 10-min intervals, 12910 clear-sky records for tilt β =30° and 20623 records for tilt β =45° were selected. Fig. 5 shows the diffuse fraction, $f_d = DHI/GHI$ versus the clearness index k_t (GHI normalized by the horizontal extraterrestrial irradiance), with the discarded data greyed out and the selected clear-sky samples highlighted in red for the PIM experiment. Fig. 6 shows how the clear-sky detection algorithm operates on a GHI series.



Fig. 6: 1-min GHI time series, with the clear samples highlighted in red, for the PIM site.



Fig. 7: rRMSD obtained by comparison of measured GTI and the Perez model's estimate, as a function of the surface azimuth, for two tilted planes with different nominal azimuths. Data from the PIMENT experiment.

3.2.2 Examples of the optimization procedure

Two examples of the optimization procedure which leads to the best surface azimuth are shown in Fig. 7, both showing that the rRMSD has a well defined minimum and the target azimuth is accurately determined. In (Barbier et al. 2019) this method was applied in the context of a large PV array in a two dimensional space (tilt, azimuth) using Mc Clear (Lefèvre et al., 2013) estimates for clear-sky information available at CAMS. In our case, ground measurements for GHI, DHI and DNI are used and the tilt angle is fixed. In contrast to method PA, this method is unable to identify changes in azimuth over time and thus should be applied only in cases in which the azimuth is fixed.

4. Results

Azimuth estimates from Method PA for all the orientations from the PIMENT experiment are shown in Figure 8, throughout the time span for this data. The azimuth estimates, standard deviations and the deviation from true value are shown in Table 3 for both datasets.



Fig. 8: Azimuth estimates for the PIMENT data using method 1. Labels are to be interpreted from Table 2.

		Method (PA)			Method (BBSD)		
Label	Dataset	γ(°)	u(°)	d(°)	γ (°)	u(°)	d(°)
G40_60E	PIM	-70.2	5.6	10.2	-60.4	0.2	0.4
G40_30E	PIM	-31.2	2.7	1.2	-27.6	0.2	-2.4
G20_30E	PIM	-25.8	4.8	-4.2	-20.6	0.3	-9.4
G45_0	LES	-1.3	1.8	1.3	-0.9	0.2	0.9
G40_0	PIM	-1.3	1.2	1.3	0.0	0.1	0.0
G30_0	LES	-1.5	1.5	1.5	-2.0	0.2	2.0
G20_0	PIM	-1.3	2.8	1.3	1.8	0.2	1.8
G40_60W	PIM	58.0	6.1	-2.0	49.0	0.1	-11.0
G40_30W	PIM	28.1	2.5	-1.9	27.5	0.0	-2.5
average		-	3.2	2.8	-	0.2	3.4

Tab. 3 Estimated azimuths γ for all orientations, together with their respective uncertainty u, given by the standard deviation of all the estimated azimuths for method PA, and by the standard deviation σ from the cross-validation procedure for method BBSD. Also included, the difference *d* between the estimated azimuth and the nominal value. The last row shows the absolute average of u and of the deviations.

As can be seen from Figure 8, if surface azimuth variations occur over time, method PA can detect those changes while method BBSD can be used on sub-intervals with well defined azimuth, provided GHI and diffuse fraction data is available.



Fig. 9: Standard deviation from method 1 as a function of the nominal azimuth of the surface, for the 40° tilt surfaces (PIMENT).

The standard deviation of method PA (shown as u in Table 3) describes the variability of the estimated azimuth over time. If the nominal azimuth is known to be fixed over this time period, this observed variability can be used as the true uncertainty for the method. Its average value of 3.2° is similar to the average absolute deviation of the method. This uncertainty increases with the surface azimuth (see Fig. 9 for the 40° tilt experiments). Since only a few tilt angles have been considered, there is no clear evidence of a similar

dependence on the uncertainty with surface tilt.

The statistical standard deviation of method BBSD (shown as u in Table 3) is an order of magnitude smaller than the observed deviations and therefore is not useful as an uncertainty estimate. Finally, the absolute deviations from method PA are smaller in most cases than those from our implementation of method BBSD.

5. Conclusions

Two methods for the estimation of surface azimuths were implemented and validated against data from tilted surfaces with nominal azimuth values between 60° East and 60° West. The first method (labelled PA) is new and it allows to estimate the surface azimuth using only 1-minute resolution GTI data and clear sky estimates from a reliable model. The method also provides the estimated uncertainty, if the azimuth is known to be fixed for the duration of the GTI measurements. If changes in azimuth take place, the method can detect these changes over time. This makes it a useful method to perform quality checks on remote measuring stations which can be affected by severe weather conditions. The accuracy of this method is similar or better than our implementation of a second method (labelled BBSD), based on horizontal measurements of GHI and its diffuse fraction.

The PA method cannot be used to detect azimuth orientations of surfaces that are not facing the sun (i.e. azimuths greater than 90°), since it relies on the existence of a maximum on the GTI curve for clear days. For small misalignments, the usual scenario in several applications, this method performs well, with an average uncertainty of 3.2° over several tested orientations. Its uncertainty increases with the nominal azimuth of the surface, and for the - 60° surface azimuth (east-oriented), the departure of the estimate from the nominal value (d) is larger than the uncertainty u.

The BBSD method (also evaluated here) is unable to detect changes of azimuth over time, but it is less complicated in terms of calculations. It requires ground data for GTI, GHI, DHI (or DNI), or clear-sky satellite estimates. The time resolution of the data is not a critical issue.

Both methods of azimuth estimation are complementary, in the sense that they differ in strengths and weaknesses. Work is underway in order to refine the first method and address the cases where there's conflicting outputs between the two methods, especially for large azimuths.

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L-04. Solar Resource Management and Applications

SOLAR ENERGY POTENTIALS TO DEVELOP POWER DEVICE SIZING AND INTEGRATION FOR SOLAR-POWERED AIRCRAFT (UAV) APPLICATION

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Abstract

Solar-powered aircraft use solar energy as a source of energy to power the aircraft. Solar aircraft has limited capacity to harness the available solar energy and lacks proper power device sizing. Photovoltaic geography information system software was employed to harness solar energy and obtain Malaysia's solar radiation model. The model developed an energy balance and mission path to effectively conserve solar energy for efficient solar aircraft performance. Power device sizing was designed with the required PV cell as 32 and rechargeable battery as 74. The power device is integrated into the aircraft, the PV cells on the wings, and the batteries are inserted in the aircraft's fuselage.

Keywords: Solar radiation model; solar-powered aircraft; power device sizing; integration and Applications.

1. Introduction

Photovoltaic geographic information systems (PVGIS) is free software that provides solar energy potentials in photovoltaic (PV) systems. The software provides solar energy potentials worldwide. The software harness the solar radiation model of a particular region and country (PVGIS, 2019). The solar radiation model is used to develop a solar energy balance and mission path diagram for solar aircraft unmanned aerial vehicles (UAV) (Mattos, Secco, & Salles, 2013), (Safyanu, Omar, & Abdullahi, 2018).

Solar aircraft use solar energy as a source of power to airborne. The PV cell, rechargeable battery, and maximum power point tracker (MPPT) are termed as the power device (PD) and are the main components that power the motor and propeller that provides a thrust that airborne the aircraft (Safyanu, Abdullah, & Omar, 2019).

Solar aircraft have limitations in harnessing the available solar energy required to fly the aircraft for a long time. Also, the rechargeable battery energy density is very low when compared to fossil fuel. To effectively and efficiently fly solar aircraft for medium and high altitude and long-endurance (HALE), the power device needs to be sized accordingly (Safyanu et al., 2019). The proper power device sizing ensured the number of PV cells and rechargeable batteries required to fly the aircraft is calculated. Consequently, a particular region or country's solar radiation model is crucial for developing the mission path diagram's solar energy balance (Wei, Yao, & Xie, 2020) and (Danjuma, Omar, & Abdullahi, 2021). These provide the utilisation of solar energy and the path for the aircraft to airborne to conserved energy.

This paper aims to harness solar energy potential using PVGIS software to provide a solar radiation model for Malaysia to develop a solar energy balance and mission path diagram. And provide proper power device sizing for solar aircraft unmanned aerial vehicles (UAV) for medium and high altitude and long endurance.

2. Methodology

2.1 Photovoltaic geographical information system

PVGIS software is freely available online developed by the European Commission's science and knowledge service. The software comprises three tools: PV performance, solar radiation, and typical meteorological year (TMY); Figure 1 shows the tools. The PVGIS potential includes:

- PV perspective for diverse technologies and capabilities of grid-connected and stand-alone systems.
- Solar radiation and temperature, as monthly averages or daily profiles.
- Full-time series of hourly values of both solar radiation and PV performance.
- TMY data for nine climatic variables.



Fig. 1: PVGIS tools

Figure 2 depicts the PVGIS software window used to provide the solar radiation data for a particular region of the world at a specific time. The software PV performance includes the grid-connected, tracking PV, and the off-grid. The data are monthly, daily, and hourly.



Fig. 2: PVGIS software window

The PVGIS software is used to provide the solar radiation model for Malaysia. The model will be verified with 6th order polynomial. The model will harness Malaysia's solar energy potential and developed the energy balance and the mission path diagram. The energy balance is the average yearly daily available energy of Malaysia and its utilisation to ensure efficiency. However, the mission path is a profile to utilising solar aircraft's available daily energy to ensure efficiency.

2.2 Development of Power Device Sizing

The next stage of the methodology is to develop power device sizing to provide the PV cells and the battery required to efficiently power the solar aircraft. Lastly, the power device is integrated into solar aircraft as a power source to propel the aircraft (Danjuma et al., 2021).

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The (PD) is the primary energy for solar aircraft (UAV). Aircraft configurations; total mass of the aircraft, wingspan, and chord are adopted from articles and improved. Aerodynamic characteristics are the lift and drag coefficients (airfoil, induced, and parasitic drags inclusive). And the average annual daily solar radiation for Malaysia. The parameters were integrated into the MS Excel program as input variables and other required input variables shown in Table 1 to calculate the PD sizing, such as the required number of PV cells and the aircraft's rechargeable battery (Danjuma et al., 2021).

Constants /Variables	Value	Units	Notes
CL	0.913	-	Airfoil lift coefficient
C_{D-afl}	0.008	-	Airfoil drag coefficient. To be added to the parasitic & induced drag
CD- Parasitic	0.0065	-	Parasitic drag
e	0.9	-	Oswald's efficiency factor (assumed value)
ρ_{air}	1.1655	Kg/m3	The density of air at 500m altitude
I _{max}	825	W/m2	Maximum sun irradiance (PVGIS, 2019) (a typical value for Malaysia)
k _{bat}	700	Wh/kg	The energy density of LS battery (assumed value)
k _{sc}	0.32	Kg/m2	The mass density of solar cells (based on ((Noth, 2008))
k _{enc}	0.26	kg/m2	The mass density of encapsulation (based on ((Noth, 2008))
k _{mppt}	0.00047	kg/W	Mass/power ratio of MPPT (based on ((Noth, 2008))
k _{prop}	0.008	kg/w	Mass/power ratio of the propulsion system (based on ((Noth, 2008))
m _{av}	0.15	kg	Mass of avionics system (based on ((Noth, 2008))
m _{pld}	0.05	kg	Mass of telecommunication payload (based on ((Noth, 2008))
η_{bec}	0.65	-	The efficiency of the step-down converter (based on ((Noth, 2008))
η_{wth}	1	-	Weather factor, which reduces the energy captured. Value of 1 is the clear sky (assumed value)
η_{sc}	0.169	-	The efficiency of solar cells (based on ((Noth, 2008))
η_{cbr}	0.90	-	The efficiency of curved solar panels (based on (Noth, 2008))
η_{chr}	0.95		The efficiency of the battery charge (based on (Noth, 2008))
η_{ctr}	0.95		The efficiency of the motor controller (based on (Noth, 2008))
η_{dchr}	0.95		The efficiency of battery discharge (based on (Noth, 2008))
η_{grb}	0.97		The efficiency of the gearbox (based on ((Noth, 2008))
η_{mot}	0.85		The efficiency of the motor (based on (Noth, 2008))
η_{mppt}	0.97		The efficiency of MPPT (based on ((Noth, 2008)))
$\eta_{\rm plr}$	0.85	-	The efficiency of the propeller (based on ((Noth, 2008))
Pav	1.5	W	Power for avionics (based on Noth 2008)
P _{pld}	0.5	W	Power for telecommunication payload (based on (Noth, 2008))

Tab 1: Variable and constant (PVGIS, 2019), (Noth, 2008)

Constants /Variables	Value	Units	Notes
T _{day}	43200	s	Day duration (based on (PVGIS, 2019))
T _{night}	43200	S	Night duration (based on (PVGIS, 2019))

However, the calculations of daily solar energy, mechanical power, total electrical power, total electrical energy and solar cell area Equation 1 to 7 were used, adopted from (Noth, 2008). The variables/constants and equations were adopted from (Noth, 2008) because they reflect current PV technology (in respect to power device sizing of solar aircraft).

Daily solar energy =
$$\frac{l_{max}T_{day}}{\pi/2} A_{SC} \eta_{wthr} \eta_{sc} \eta_{cbr}$$
 (eq. 1)

Where; η_{sc} = solar cell efficiency, η_{cbr} = cambered efficiency, η_{mppt} = MPPT efficiency, I_{max} = maximum irradiance, A_{sc} = solar cell area and T_{day} = the day duration.

Mechanical power =
$$\frac{C_D}{C_L^{3/2}} \sqrt{\frac{(mg)^3}{s}} \sqrt{\frac{\rho}{2}}$$
 (eq. 2)

$$C_D = C_{D afl} + C_{D ind} + C_{D par}$$
(eq. 3)

Where; C_L = lift coefficients, C_D = drag coefficients, $C_{D \ afl}$ = drag coefficient airfoil, $C_{D \ ind}$ = drag coefficient induced, $C_{D \ par}$ = drag coefficient parasitic, ρ = air density, S = wing area, and v = aircraft's relative speed.

Electrical power =
$$P_{mech} \frac{1}{\eta_{mot} \eta_{ctrl} \eta_{grb} \eta_{plr}}$$
 (eq. 4)

Where; P_{mech} = mechanical power, η_{mot} = motor efficiency, η_{ctrl} = motor controller efficiency, η_{grb} = gearbox efficiency and η_{plr} = propeller efficiency.

Total electrical power =
$$P_{Eflight} + \frac{1}{\eta bec} (P_{av} + P_{pld})$$
 (eq. 5)

Where; $P_{Eflight}$ = Electrical power, P_{av} = Avionics power, P_{pld} = payload power. and η_{bec} = BEC (Battery Elimination Circuit) efficiency

Total electrical energy =
$$P_{elec\ tot}\left(T_{day} + \frac{T_{night}}{\eta chrg\ \eta dchrg}\right)$$
 (eq. 6)

Where; $P_{elec\ tot}$ = total electrical power, $\eta chrg$ = the charge efficiency, $\eta dchrg$ = discharge efficiency of the battery for the night period, T_{night} = the night duration and T_{day} = the day duration

Solar cell area =
$$P_{Etot} \frac{\pi}{2\eta_{sc} \eta_{cbr} \eta_{mppt} \eta_{wthr}} \left(1 + \frac{T_{night}}{T_{day}} \frac{1}{\eta_{chrg} \eta_{dchrg}}\right) \frac{1}{I_{max}}$$
 (eq. 7)

Where; P_{Etot} = total electrical power, η_{sc} , = solar cell efficiency, η_{cbr} = cambered efficiency, η_{mppt} = MPPT efficiency, η_{wthr} = efficiency of the solar cell in different weather conditions, T_{day} = day duration, T_{night} = night duration, $\eta chrg$ = the charge efficiency, $\eta dchrg$ = discharge efficiency of the battery for the night period, and I_{max} = the maximum irradiance.

2.2.1 Calculation of the Number of Solar Cells for the Design

The required number of solar cells is calculated from the daily solar energy available with the flight profile mission's duration and the peak solar hour (PSH); it is the day that the solar intensity is high (Li, 2019) & (Chiras, 2020).

Solar cell wattage =
$$\frac{\text{Daily Energy}}{PSH}$$
 (eq. 8)

No. of solar cell =
$$\frac{solar cell wattage}{solar cell power}$$
 (eq. 9)

2.2.2 Calculation of Number of batteries for the design

The number of batteries in the design is a function of the daily energy available for the autonomous days of the non-availability of solar radiation (Dwivedi, Kumar, Ghosh, & Kamath, 2018) and (Danjuma et al., 2021)

$$Ampere hour = \frac{Available \ daily \ Solar \ Energy}{Battery \ Charge \ Voltage}$$
(eq. 10)

Number of batteries =
$$\frac{Ampere Hour (Ah)}{Battery Nominal capacity(Ah)}$$
 (eq. 11)

3. Results and Discussions

3.1 Solar radiation model of Malaysia

The solar radiation model for Malaysia was obtained from photovoltaic geographic information software data for Malaysia, 2019, as shown in Table 2, and Figure 3 shows the solar radiation map for Malaysia. The model (solar radiation data from PVGIS) was validated using the 6th polynomial. The coefficient of correlation has a value of $R^2 = 0.998$. which shows that (solar radiation data from PVGIS) is 100% convergence and positive, as shown in Figure 4. The maximum irradiance I_{max} of the annual daily average was found to be 825W/m² (the cloudness was taken into consideration), and the time duration for the availability of solar radiation (T_{day}), was 12 hours (PVGIS, 2019). The data is incorporated into the MS Excel program to calculate the PD sizing of solar aircraft. However, the model was used to develop the energy balance and the mission path for both Malaysia.

Time (h)	7	8	9	10	11	12	13	14	15	16	17	18	Total	Average
Month					Radia	tion (V	W/m^2)							
January	335	299	512	677	752	755	759	651	529	412	239	92	6012	501
February	216	309	582	759	822	853	807	730	550	401	299	113	6441	536.8
March	213	281	535	701	795	819	785	650	524	370	258	83	6014	501.2
April	217	334	570	725	796	811	795	673	552	382	221	53	6129	510.8
May	225	351	568	669	722	754	739	641	512	388	226	38	5833	486.1
June	164	295	510	652	716	754	732	679	554	453	247	64	5820	485
July	151	246	464	618	687	722	732	671	576	437	288	85	5677	473.1
August	172	251	500	625	705	740	689	609	537	394	245	72	5539	461.6
September	195	214	485	645	730	731	705	620	508	383	219	38	5473	456.1
October	194	282	515	677	784	775	702	564	434	302	157	4	5390	449.2
November	208	343	570	671	753	761	692	548	420	270	137	2	5375	447.9
December	251	258	470	616	693	702	663	604	407	279	208	38	5189	432.4

Tab 2: PVGIS solar radiation data 2019 for Malaysia



Fig. 3: Solar radiation map of Malaysia



Fig 4: Solar radiation model for Malaysia

3.1.1 Energy balance

The energy balance is a graphical representation of the daily solar energy obtained which was calculated as 578.33 Wh using Equation 1 within 12 hours from Malaysia's solar radiation model, as shown in Figure 5. The green line is the solar energy collected with the period of 6 am to 6 pm. And the yellow line is the excess energy stored in the battery. Also, the energy balance depicts the utilisation of solar energy to power the solar aircraft during the day. And the excess energy is stored in the rechargeable battery to power the solar aircraft at night, while the blue line is the energy used from the battery. At the same time, the red line is the total electrical power required by aircraft 18 W.



Fig 5: Solar energy balance for Malaysia.

3.1.2 Mission path

The mission path is a profile used to launch the solar aircraft based on the available solar energy collected from Malaysia's solar radiation, as shown in Figure 6. The mission is designed for medium and high-altitude missions to efficiently conserve energy. The mission was launched at 7 am and climbed to an average altitude of 500 m when solar energy is available and dwells at the altitude. After 6 am when solar energy starts to diminish, the aircraft cruise to a lower altitude of 200 m and dwell all through the night. And move to the higher altitude in the morning continuously until the mission is terminated.



Fig 6: Mission path

3.2 Developed power device

Table 3 presents the result of the power device sizing for solar-powered aircraft. Aircraft configurations, aerodynamic characteristics, and the average annual daily solar radiation for Malaysia were used as the input variable integrated into MS Excel. The output variable determined the number of solar PV cells and rechargeable batteries for the design.

Input Va	riable		Output Variable				
Parameter	Value	Units	Parameter	Value	Units		
Mass (m)	3	Kg	Mechanical Power	10.92	W		
Wing Span (b)	3.2	m	Total Electrical Power	19.47	W		
Chord (a)	0.3	m	Total Electrical Energy	465.55	Wh		
Radiation (H)	825	W/m^2	Daily Solar Energy	578.33	Wh		
Aspect Ratio (AR)	11.25	-	Solar Cell Area	0.62	m^2		
Lift Coefficient (CL)	0.913	-	Total Wattage	107.09	W		
Drag Coefficient (CD)	0.047	-	No. of Solar Cell	32	-		
Velocity	10	m/s^2	No of Battery	74	-		
			Total Mass	2.72	kg		

Tab. 3: Design of Power Device Sizing for Solar-Powered Aircraft Table

3.2.1 Integration of power device to the solar-powered aircraft

The power device sizing was derived from Equations 9 and 11 used to calculate the number of PV cells as 32 and the number of batteries as 74, respectively. Table 3 depicts the input variable used to calculate the power device sizing of the solar-powered aircraft and the output variable of the results. Figure 7 shows the integration of the power device for solar-powered aircraft applications.



Fig. 7: Integrated power device for solar-powered aircraft

4. Conclusion

PVGIS harnessed solar energy potentials and obtained solar radiation data for Malaysia, and the data was used to develop a model. The model was used to develop both the energy balance and mission path for Malaysia. The energy balance displays the solar energy collected during the daytime from 6 am to 6 pm. The available energy is calculated as 578.33, and the required power is 18 W. The mission path provides an avenue in which the aircraft can take off and navigate from a minimum of 200 m to a maximum of 500 m to conserved energy. The Power device sizing provides the number PV cell as 32 and the rechargeable as 74. The power device was integrated into the solar-powered for effective and efficient application of the solar-powered aircraft.

5. Acknowledgments

I will like to use this opportunity to thank my supervisor, Associate Professor Zamri Omar and co-supervisor Dr Mohd Noor Abdullah for their contribution and guidance. Also, I am grateful to my employer and tertiary education trust fund (TETFUND) for providing funds for my studies. This paper was possible because of your support and encouragement.

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Detailed analyses of meteorological time series for the sizing of storages in renewable energy systems - uncertainties related to inter-annual and database to database variabilities

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Abstract

The sizing of the generation capacity and the storage devices necessary to guaranty certain levels of autonomy and security of supply in solar energy systems shows a high sensitivity to details in the evolution of the driving meteorological parameters. For increased reliability with quantified uncertainty the use of multi-annual time series and is mandatory. Here a multi decadal set is used to inspect the sensitivity to details of irradiance series and the length of the time series inspected on the sizing of a PV plus storage system for an autonomous power supply system. In addition, the variability of sizing results when using data bases from different sources – satellite derived data and data stemming from reanalysis schemes is analyzed. The data applied refer to the location Faroe Islands.

Keywords: System sizing, stand alone system, solar radiation data, variability

1. Introduction

Identifying configurations for a secure coverage of the load in island grids by means of wind or solar power, leads to the need for the inclusion of storage capacity and/or a remarkable oversizing - with respect to the generation capacity needed to assure equality of annual generation and load) – of the renewable generation park. The selection of reasonable combinations of storage capacity and oversizing is usually done by use of time step simulations based on at minimum annual data sets of the meteorological conditions. The interannual variability of the meteorological conditions causes a sensibility of the system sizing to the specific set of of input data selected. There is a broad body of literature discussing the variation of the long term, annual or monthly irradiance sums and the resulting PV generation capacities. The respective discussion of the sizing of the storage capacity for PV systems to reach a desired security of supply is discussed less frequently.

Here, a multi-decadal series of irradiance data with daily time resolution is used to inspect the sensitivity of the sizing of storage devices in stand-alone PV systems designed for the supply of a summertime-only load, to the peculiarities of such a set. In addition, time parallel decadal sets, stemming from different data bases are used to look for the variability of the respective data base specific sizing outcomes.

2. Short view on status of sizing procedures and meteorological input data applied

Examples for the sizing of generation and storage capacity of respective of systems with various capacities are discussed since several decades. Examples are e.g., given by Lund and Mathiesen 2009, Nitsch 2010, Esteban. Zhang and Utama 2012, Cabrera, Lund and Carta 2018, Katsaprakakis and Voumvoulakis 2018, Trondheim et al. 2018, Lund 2018, Bogdanov and Breyer 2018, Dowling et a. 2020. These procedures require sets of meteorological data which reasonably should have a minimal length of one year, that typically form the bases of a time series simulation scheme to track the systems performance depending on the setting of the capacities. The capacities are subsequently varied to approach the desired system performance-

The length of the time periods analysed varies from 1 to up to 30 years, depending on the availability of sets of meteorological data. The selection of these sets and their basic properties – especially their length has been recognized as a critical issue, see.g. Heide et al 2010, Thevenard, D S. Pelland. 2013, Pfenninger and Staffell

2016, Pfenninger 2017, Bryce et. 2018, Sengupta et al. 2018, Rinaldini et al. 2021, Kies et al. 2021 and, for the case of projected future data sets, Jerez et.al 2015. In this context there is a broad discussion on the year-to-year variability of the annual irradiance sum and thus the expected annual PV generation. In contrast, the interannual variability of challenges for the storage systems connected to the occurrence of extended periods of low generation due to overcast situations has received less attention.

3. Irradiance data, system modeling and sizing schemes applied here

This issue will be discussed based on a multi decadal set of data of the daily irradiance sum and co-located decadal sets stemming from different data bases. Focus is on the sensitivity of the layout of PV/storage system mentioned, to the length of sub-sets selected from this base.

These examples will be performed using a simple model working with a daily timestep that assumes loss-less operation. The meteorological conditions selected refer to the Faroe Islands, located in the Northern Atlantic at ~62°N, ~7.5°W (see fig. 1).. It's the intention that the results should also cast a light on the requirements on the quality of predictions of future meteorological conditions to reflect details of the statistics of the data sets.



Fig. 1: Map showing thr location of the Faroe Islands, about 400 km north of Scotland.

For the Faroe Islands a 56-year data set with meteorological observations comprising synoptic cloud cover is available. The years 1958-2013 are covered here. Satellite derived irradiance data from the SARAH data base (Müller et al. 2015) are used to calibrate a model giving daily irradiance sums from the cloud cover observations, see Beyer 2020. There a model for the daily PV generation in dependence of the daily irradiance sum based on monitored data of a small PV system on the Faroe Islands, is applied to complete the modelling scheme for the PV generation.

The system analyzed in the next section refer to PV/battery system sized for the safe supply of a fixed load during the summer months May to August. It is assumed, that the load is disconnected for the rest of the year, while the PV stays connected allowing for a fully charged battery at 1st of May. Losses are neglected.

The sizing scheme starts with a setting of the PV generation capacity. The basic sizing is given by the generation capacity to assure equal long-term generation and consumption in the summer months, termed PV-size 1. For the determination of the storage size required for complete load coverage, given a certain generation capacity, a method derived from a scheme given by Haas 94 is used. The storage size required for save supply is estimated by analyzing the evolution of the cumulated balance of generation and load for the period inspected. (see e.g. Beyer 2020, Luther and Gabler 1988). The storage requirements can be assessed by the analysis of the relative maxima and minima of the balance series. They are expressed here by multiples of the daily load consumption [days of load].

4. Results

4.1 Analysis for a multidecadal data set

The scheme is applied first to identify the storage size necessary complete load coverage over the 56-year period, given the PV-size 1. Figure 2 gives for illustration the section of the respective balance process for first two years analyzed.



Fig. 2: Section (first 2 years) of the cumulative balance process for a system with PV-size 1 (i.e., equal average generation and load for the period May to August). The periods with active (Mai-August) and inactive load can be recognized. Relative minima occur end of August.

From this section a requirement of ~11.5 days of load can be identified from the max difference of local minima and previous maxima (occurring here for days 204 and 247 resp.). The analysis of the complete set results in a required storage size of ~13.5 days of load. The evolution of the content of a storage of that size is given in figure. 2 for the complete set.

The situation defining that storage requirement appear end of September 1997. For the specific system analyzed here, the appearing local minima in storage content relate to individual years. From this presentation the storage requirement that would result from the analysis of the data for individual years of sections of years can be directly assessed It is visible that challenges for the storage show large variations over the years.



Fig. 3: The evolution of the content of a storage with a capacity of ~13.5 [days of load] for a system with average generation capacity equal to the load in the period May to August over the 56-year period analyzed

Oversizing the generation capacity by a factor of 1.1 results in a reduction of the required storage capacity to ~ 10 days of load (fig. 3). It can be noticed that the pattern of the challenges changes with the changes in the PV size. The required storage size is now defined by the situation in another year.



Fig. 4: Same as fig.3 but for a system with PV oversized by a factor of 1.1 and a required storage capacity of 9.8[days of load]

Further increase of the PV-size by sizing factors of 1.2 (fig.5) and 1.5 (fig.6) result in identifying year 1958 as the storage defining one, givin required storage sizes of 7.4 for sizing factor 1.2 and 3.8 for sizing factor 1.5.



Fig. 5: Same as fig.3 but for a system with PV oversized by a factor of 1.2 and a required storage capacity of 7.4[days of load]



Fig. 6: Same as fig.3 but for a system with PV oversized by a factor of 1.5 and a required storage capacity of 4.8[days of load]

From these results, it is obvious that concepts design "design sets" fails for systems sensible for the conditions in specific months. These systems show a high sensitivity to the distribution characteristics and sequential properties of the irradiance data, linking the outcome of a sizing based on data for an individual year with a high uncertainty.

Obviously, the final storage sizing can by gained only when inspecting the PV-size specific critical year. From looking at the fig. 3-6 one can – with exception of the case given in fig. 6 – see that there are years giving required storage sizes close to the "final" case. The chances hitting these cases when inspecting not the complete set but only individual sequences of a length of 2, 5 and 10 years is given in figs. 7-9.

The curves are constructed by extracting the information of the required storage size from the storage content data for the case of the sizing actor 1.2 (fig.5), and passing (shifted by days) a sliding window of the respective length over the complete set and sampling the maximum required storage data for that position of the window. Sorting those data by size result in the plots given.



Fig. 7: Distribution characteristics for the detected required storage sizes from the analysis of 2-year sequences. A fraction of 0.2 of all sequences analyzed show a required storage size bigger than ~5.6 days of load (~75% of the ~final value.



Fig. 8: Same as fig. 7, but for 5-year sequences. A fraction of 0.2 of all sequences show a required storage size bigger than ~6.8 days of load.



Fig. 9: Same as fig. 1, but for 10-year sequences. A fraction of ~0.3 of all sequences show a required storage size bigger than ~6.8 days of load.

These findings show that, due to the sparseness of occurrence of critical situations, the probability for encountering years standing for enhanced storage requirements is limited, even with longer sets used for inspection. The uncertainty of the sizing for save supply may be assigned with the help of analyses like this, A respective tolerance for handling low probability loss of power events is as well needed.

4.2 Analysis for decadal data sets from diverse data bases

As mentioned, in addition to the uncertainties arising from the intrinsic temporal variability of irradiances, the uncertainties in measured and/or estimated radiance data add to the uncertainties in system sizing.

To inspect the resulting variability, here radiance data sets offered by the PV-GIS server (PVGIS 2021) are used. In detail, data stemming from satellite observations and derived from reanalysis schemes, consisting of the sets:

- PVGIS-SARAH, satellite derived, marked SC

- PVGIS-ERA5, reanalysis product, marked E5
- PVGIS-COSMO-REA6, reanalysis product, marked CO

for the year 2005-2015 are used. Table 1 gives the irradiation conditions for the location Tórshavn,

Tab. 1: irradiation conditions at Tórshavn, Faroe Islands, from databases offered by the PV-GIS server (see text)

	SC	E5	C0
average annual irradiation [kWh/m ²]	692	832	821

The data, given with hourly resolution by the server, are aggregated to sets of daily irradiance sums and processed to PV generation data as described above to be in line with the previous analyses scheme. The calculations of the generation to load balances are done with a consumption equal to PV average generation in the summer month (PV-size 1).

As a result, from the storage sizing for the 11-year data base SC fig.10 gives the evolution of the storage content for a system with PV-size 1. The required storage size was determined to be 13.78 days of load. It is visible tat also from this set the storage requirements from individual years show a high variability.



Fig. 10: The 11-year evolution of the content of a storage with a capacity of ~13.78 [days of load] for a system with average generation capacity equal to the load in the period May to August over the 11-year period analyzed. Data base: satellite derived irradiance data set SC. Required storage size identified to be 13.78 [days of load].

The application of the data stemming from the reanalysis information E5 results in a storage requirement of 15.85 days. Comparing the evolution of the storage content in this case (fig. 11) with the previous result, it can be remarked that, while besides the elevated magnitude of the storage content one can observe basically parallel pattern, except for year number for (2008). For that year the storage is remarkable more challenges based on the analyses with the SC set.



Fig. 11: Same as fig.10 but for a but for the reanalyses set E5. Required storage size identified to be 15.85 [days of load]

Fig. 12 gives the evolution of the storage content stemming from the application of the CO reanalysis set. In this case the required storage capacity is 23.33 days of load. This is remarkably higher than the values identified for the SC, E5 and the cloud cover derived set discussed in the previous section. In addition, the temporal pattern shows, that the storage size is defined by the last year, which does not stand out in the results for the two other sets. These differences are in contrast to the similarity of the annual irradiation given by the CO and E5 sets, casting doubts on the characteristics of the temporal characteristics of the CO sets.



Fig. 12: Same as fig.10 but for a but for the reanalyses set CO. Required storage size identified to be 23.33[days of load]

Fig, 13 gives storage requirements requirements detected for the individual years. The SC and E5 sets show mainly a parallel reaction to a change of year, the CO set present exceptional out-layers in two years



Fig. 13: Storage requirements identified from the data for individual years. The blue dots refer to the CO set, the orange dots to the E5 set and the grey dots to the SC set.

An analysis of the distribution of storage sizes identified on an annual basis is given in fig. 14 by the cumulative fraction of the detected storage requirement presented in fig.13. Excluding the out-layers from the CO set would result in an almost linear relation.



Fig. 14: All required storage sizes detected for individual years using the SC, E5 and CO data sets presented by the storage size as function of the cumulative fraction of the sets (a fraction of about 0.55 the years show required storage sizes smaller than 10 days of load).

Inspecting the storage requirements for oversized PV-generation shows that the relative differences of the results, including the specific results or the CO set, are basically preserved (see table 2). The temporal shifting of the storage defining years is - probably due to the difference in length of the sets less pronounced than for the multidecadal set.

PV sizing factor	PV	E5	СО
1	13.78	1585	23.33
1.1	10.75	12.56	18.20
1.2	7.72	9.34	15.76
1.5	2.84	3.27	8.45

Tab. 1: Required storage sizes identified for different PV oversizing factors applied on data from the PV, E5, and CO sets.

5. Conclusions and Outlook

The examples given should show that the sizing of the storage components of renewable energy systems for autonomy show a high sensitivity to the details of the time series selected for the process. It can be concluded that the reliability of the sizing results (and information on the uncertainty of the expected performance) can be improved by extending the temporal coverage of the meteorological sets applied.

However, this holds only when neglecting changes in the statistical characteristics of the data as induced by climate change. In view of the expected changes in future meteorological conditions, the analysis of the dependency of system performances on details in distribution function and sequential characteristics of the meteorological sets additional requirements on schemes to generate data sets applicable for energy system planning (for context see e.g. Jerez et al. 2015, Jerez et al. 2019).

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L-05. Solar Resource Forecasting

Performance assessment of the ECMWF solar irradiation forecast in the Pampa Húmeda region of South America

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Abstract

The increase in solar power generation has a direct impact on the management of the electrical grids, therefore knowing the resource availability for the next few hours and days becomes essential. In this article we present a performance evaluation of the solar predictions provided by the European Centre of Medium-Range Weather Forecasts (ECMWF) in different sites of the Pampa Humeda region, located in southeastern South America. It is found that the intraday hourly rRMSD ranges, on average, between 24.8% and 35.5% depending on the forecast horizon. For the daily integrated values, an increasing rRMSD trend between 16.6% and 21.3% is found for 1 to 3 days ahead, respectively. No significant geographical difference of the performance is observed between the sites. The uncertainty of this forecast model is lower than other numerical weather models previously evaluated in the region, which is consistent with international studies in other regions.

Keywords: solar forecast, NWP, GHI, ECMWF, Pampa Húmeda.

1. Introduction

The large deployment of grid-connected solar energy requires the ability to handle the fast fluctuations of the resource due to cloudiness variations. One way to accomplish this is to forecast the future resource, so an intelligent system reserves management can be done by grid operators. The uncertainty of the forecast directly translates to the decision-making process for optimal electricity dispatch and commercialization, thus impacting costs and revenues (Bridier et al. 2014; Lorenz et al., 2009). The development of accurate solar irradiation forecasting methods is then an important matter to further increase the solar energy shares into electricity grids. Consequently, evaluating the prediction data that is available for a region is considered to be of high value, as it provides an initial uncertainty reference (Yang et al., 2020). The determination of this uncertainty in most areas of studies consists of comparing the forecast outputs with ground-based measured data, which also have an error associated with the accuracy of the measurement (Blaga et al., 2019; Pérez et al., 2013).

There exist several methods to generate a solar forecast, namely, Numerical Weather Predictions (NWP), solar nowcasts based on geostationary satellite images or ground-based cameras, and machine learning strategies that attempt to learn from the previous data history or to combine different sources of forecast. NWPs, the subject of this work, address the forecast up to several days ahead with an hourly time resolution. This is achieved by using numerical atmospheric physical models that simulate the near future evolution of the atmosphere's state based on initial and boundary conditions, usually obtained by remote sensing strategies (atmospheric soundings, satellite retrievals, etc.). NWPs are known to outperform other sources of intra-day solar forecasts for the prediction above 5h ahead (Lorenz et al., 2007; Perez et al., 2010), in particular, hourly satellite nowcasts and machine learning techniques based solely on ground data. Furthermore, NWPs output are a required input variable for any form of day-ahead solar forecast that aims to have a competitive and reasonable performance. These models can be classified in two categories depending on their spatial scale, as different approximations hold true in the atmosphere's system equations: global models (i.e. GFS, ECMWF, etc.) and regional or mesoscale models (i.e. WRF, NAM, etc.), whose application is restricted to a regional area. The spatial and temporal resolution of such models are limited by the available computational capacity.

In this work we assess for the south-east of South America the solar predictions' uncertainty of the global model run by the European Center for Medium-Range Weather Forecast (ECMWF). The assessment is done for global solar irradiation at a horizontal plane (GHI) using controlled-quality ground measurements distributed in the region and without applying any post-processing technique to the forecasts. The evaluation includes the forecast up to 3 days ahead at hourly and daily-integrated time bases and incorporates an uncertainty analysis that discriminates the performance by the actual sky condition. A set of well-known statistical performance metrics are used for the assessment to facilitate comparison with other studies.

This article is organized as follows. Section 2 describes the GHI ground measurements being used, which are distributed throughout the Uruguayan territory and are representative of the wider Pampa Húmeda region of southeastern South America. Section 3 presents the main user-related characteristics of the ECMWF model, the persistence reference used here as benchmark and the performance metrics used for the evaluation. Section 4 presents the main results, which are divided into the hourly forecast evaluation and daily integrated forecast evaluation with and without sky conditions discrimination. Finally, Section 5 summarizes our conclusions.

2. Ground measurements

The measuring sites are presented in Tab. 1. These stations correspond to a field solar measurement network distributed in the Uruguayan territory and are located in rural or semi-rural environments. The sites are representative of the subtropical Pampa Húmeda region. This region is identified as Cfa in the updated Köppen-Geiger climate classification (Peel et al., 2007), being warm, temperate and humid with hot summers, and has an intermediate solar short-term variability (Alonso-Suárez et al., 2020).

The measuring stations are equipped with Kipp & Zonen Class A or B1 pyranometers according to the ISO 9060:2018 standard and receive monthly maintenance. These pyranometers are calibrated every two years, as recommended by the guidelines of the World Meteorological Organization, and following the ISO-9847:1992 standard by comparison with a Secondary Standard traceable to the World Radiometric Reference. The GHI data is recorded at a 1-minute interval, from which the 1-h averages were calculated. A basic quality control of the measurements was performed, based on the clearness index and the BRSN filters (McArthur, 2005). Under optimal operation conditions, the uncertainty assigned by the manuafacter to the equipments being used is of 2-3% on a daily scale. Given the current monthly routine maintenance and our regular inspections to the measuring sites, we assign a slightly higher effective uncertainty, between 4-5% (Laguarda et al., 2020). This value is also well below the uncertainty of the forecast to be evaluated.

Site	Code	Lat. (deg)	Lon. (deg)	Alt. (m)
Salto	LE	-31.28	-57.92	42
Artigas	AR	-30.40	-56.51	136
Tacuarembó	TA	-31.71	-55.83	140
Canelones	LB	-34.67	-56.34	32
Rocha	RC	-34.49	-56.17	24
Colonia	ZU	- 34.34	-57.69	81
Treinta y Tres	PP	-33.26	-54.49	58

Tab. 1: Details of the measurement stations used in the work.

3. NWP model and performance metrics

The ECMWF runs its global forecast model at 00 UTC each day, providing hourly forecasts of GHI up to several days ahead with a spatial resolution of $0.125^{\circ} \times 0.125^{\circ}$ on latitude and longitude (approx. 14 x 14 km² in our region). We retrieved the first 72 hours of this forecast (3 days ahead) for each location of Tab. 1 and for the 2017-2018 period (two complete years).

As recommended (Yang et al., 2020) we use the clear-sky index (kc = Gh/Gh,csk) persistence as a reference to assess the performance of the forecasts. The GHI clear sky data (Gh,csk), required to compute the clear-sky index values, were downloaded from Copernicus Atmosphere Monitoring Service. This web service provides for free

clear sky irradiances estimates, derived from the McClear Model (Lefèvre et al., 2013). Any persistence reference involves the assumption that the atmospheric conditions are stationary in some sense. Here, since a days-ahead forecast is considered (issued during the previous night of the current day), the clear-sky index values of the previous day are persisted (calculated from the GHI measurements). For the hourly reference, the hourly clear sky daylight profile of the previous day is used, and for the daily-integrated evaluation, the daily clear sky index of the previous day is used, calculated as the ratio of the independent daily integration of Gh and Gh,csk.

To quantitatively evaluate the performance of the deterministic ECMWF forecast, we used common metrics (Yang et al., 2018): mean bias deviation (MBD), mean absolute deviation (MAD), root mean square deviation (RMSD) and forecasting skill (FS). The first metric measures the systematic bias of the forecast as compared to the measurements. The second and third metrics measure the dispersion of the deviations with different weighting norms, being the larger deviations more penalized by the RMSD than by the MAD. The last metric, FS, quantifies the gain of the method in terms of RMSD compared to the persistence benchmark. The metrics MBD, MAD and RMSD are defined in Eqs. (1), (2), (3), respectively:

$$MBD = \frac{1}{N} \sum_{l=1}^{N} (\hat{y}(i) - y(i))$$
 (eq. 1)

$$MAD = \frac{1}{N} \sum_{I=1}^{N} |\hat{y}(i) - y(i)| \qquad (eq. 2)$$
$$RMSD = \sqrt{\frac{1}{N} (\hat{y}(i) - y(i))^2} \qquad (eq. 3)$$

where \hat{y} are the predicted values, *y* are the ground measured data and *N* is the number of observations. The relative values of these metrics, rMBD, rMAD and rRMSD, can be expressed as a percentage of the ground measurements average. In the case of the hourly evaluation, these relative metrics are found by using the GHI mean value for each hour of the day (an hourly daily profile of GHI). For the daily evaluation, the GHI daily average is simply used as normalization. Finally, the forecasting skill, FS, is defined as,

$$FS = 1 - \frac{RMSD_{forecast}}{RMSD_{persistence}}$$
(eq.4)

being positive if the forecast outperforms the persistence and negative if not.

4. Results

4.1 Hourly forecast evaluation

The hourly performance evaluation of the ECMWF forecast and the persistence procedure up to 3 days ahead is summarized in Fig.1 (rMDB, rMAD and rRMSD) and Fig. 2 (FS). In these figures the performance metrics are plotted against the hourly forecast horizon (see the bottom x scale) or local time (see top x scale). The solid line represents the average performance over the sites of Tab. 1 and the area in transparency represents one standard deviation of the inter-sites performance, representing the spatial variability of the assessment. Tab. 2 presents the average performance metrics of the ECMWF forecast in relative terms for the three days. For the sake of clarity, the information contained in Fig. 1, Fig. 2 and Tab. 2 is only partial, for instance, the evaluation in each site is not represented and the metrics' absolute values are not given, among other detailed information that is not included. The complete set of performance metrics for each site, in absolute and relative terms, is available to the reader in the following download link: https://les.edu.uy/RDpub/ECMWF_local_evaluation.xlsx.

The overall analysis shows that the ECMWF forecast provides a better performance around solar noon with a slight downgrade with increasing forecast horizon, especially with increasing days. The ECMWF model performance is higher than the persistence procedure in all metrics, as expected. The ECMWF model has a low bias, with a tendency to overestimate before solar noon (first hours of the day) and a tendency to underestimate

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after solar noon (late hours of the day). The trend towards underestimation increases with increasing days. The rMBD metric averaged between sites is contained between -3.7% to +3.7% for day 1, between -4.6% to 1.1% for day 2, and between -5.4% to +0.6% for day 3. The persistence procedure in all scenarios underestimates the resource, with a similar underestimation increase with increasing days. In the central hours the rRMSD of the ECMWF forecast varies between 24.9% (best, in day 1) and 37.5% (worst, in day 3). The persistence shows a similar increasing trend ranging from 36.5% (day 1) to 49.1% (day 3) around the solar midday of each day. The rRMSD variation in each day remains approximately constant for the ECMWF forecast, being of 8.8% for day 1 (24.9% to 33.7) of 8.5% for day 2 (from 27.3% to 35.7%) and of 8.2% for day 3 (from 29.3% to 37.5%). The rMAD presents similar behavior to the rRMSD, with the difference that the performance of the persistence (measured by this metric) tightens with the ECMWF model. The FS averaged between sites indicates that the performance of the ECMWF model is superior compared to the persistence procedure for all forecast horizons. Fig. 2 shows that the FS tends to decrease with increasing days and has a daily profile that peaks around the solar noon. The FS varies between 22.0% and 33.8% for day 1, between 23.3% and 33.0% for day 2 and between 21.4% and 29.6% for day 3.



Fig. 1: Performance metrics of the ECMWF forecast at hourly resolution and up to 3 days ahead.



Fig. 2: Forecasting skill of the ECMWF forecast at hourly resolution and up to 3 days ahead.

		Day 1			Day 2			Day3	
time	rMBD (%)	rMAD (%)	rRMSD (%)	rMBD (%)	rMAD (%)	rRMSD (%)	rMBD (%)	rMAD (%)	rRMSD (%)
7	+3.7	20.3	31.1	+0.8	23.2	35.7	+0.6	24.0	36.9
8	+2.9	19.5	30.5	+1.1	21.8	34.0	+0.6	22.5	35.3
9	+2.2	17.6	26.5	+0.4	19.9	30.2	-0.1	20.8	31.6
10	+1.4	16.7	24.9	+0.1	19.0	28.3	-0.3	20.0	29.8
11	+1.0	16.9	25.1	-0.7	18.5	27.3	-0.8	19.8	29.3
12	+0.2	17.3	25.4	-1.3	19.0	27.8	-1.8	20.1	29.3
13	-1.0	17.8	25.8	-2.3	19.0	27.3	-2.7	20.7	29.7
14	-2.0	18.3	26.3	-3.5	19.8	28.3	-4.0	21.4	30.5
15	-3.2	19.3	27.7	-4.6	20.7	29.8	-5.3	22.4	32.0
16	-3.7	20.6	30.2	-4.6	22.0	32.2	-5.4	23.4	34.2
17	-2.9	21.6	33.7	-4.4	22.9	35.5	-4.4	24.2	37.5
18	-1.4	21.9	32.3	-3.0	23.2	34.5	-2.9	24.3	35.9

Tab. 2: Hourly performance of the ECMWF model up to 3 days ahead.

Previous evaluations of NWPs in the region are given in Porrini et al. (2017) and Teixeira-Branco et al. (2018). These works used the WRF (Weather Research and Forecasting) mesoscale model with its initial and boundary conditions taken from the GFS (Global Forecast System) global model forecast and different parameterizations (microphysics, boundary layer, solar radiation, among others) to predict GHI in the same region of this study. Porrini et al. (2017) provides an hourly evaluation of the GFS driven WRF forecast, and found site averages of rMBD around +12-14% and rRMSD around 40-44% for day 1 close to the solar midday. The performance found here for the ECMWF forecast is significantly better.

4.2 Daily accumulated forecast evaluation

On a daily scale, the results are presented for the first forecast day by integrating the first 24h (1 day ahead), the second forecast day by integrating the hourly horizons from 25h to 48h (2 days ahead) and the third forecast day by integrating from 49h to 72h (3 days ahead). Tab. 3 shows the ECMWF model performance metrics on a daily scale and discriminating by each site, in absolute and relative terms. For compatibility with previous studies, the absolute values are presented in MJ/m². If desired, it is possible to convert them to kWh/m², by dividing them between 3.6. Tab. 4 shows the same information but averaged over all sites.

Tab. 3: Performance of the ECMWF model for daily-integrated predictions up to 3 days ahead and discriminated by each si	ite.
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	N	Mean GHI (MJ/m²)	MBD (MJ/m ²)	MAD (MJ/m²)	RMSD (MJ/m ²)	rMBD (%)	rMAD (%)	rRMSD (%)	FS (%)
LE									
day 1	718		-0.3	2.1	2.9	-1.8	12.1	16.7	57.4
day 2	717	17.5	-0.5	2.4	3.4	-3.2	14.0	19.5	58.0
day 3	716		-0.7	2.7	3.8	-4.1	15.5	22.0	58.5

AR									
day 1	702		0.0	2.9	2.9	-0.1	11.9	16.9	56.8
day 2	701	17.5	-0.3	2.4	3.5	-2.0	13.7	19.8	55.7
day 3	700		-0.4	2.6	3.8	-2.5	15.1	21.8	51.9
ТА									
day 1	724		-0.1	2.0	2.9	-0.7	12.2	16.9	57.7
day 2	723	17.0	-0.5	2.4	3.4	-2.7	13.9	20.2	57.2
day 3	722		-0.8	2.6	3.8	-4.5	15.6	22.5	54.5
LB									
day 1	724		0.0	1.9	2.6	-0.4	11.3	15.5	61.5
day 2	723	16.8	-0.2	2.2	3.0	-1.2	13.1	18.2	59.8
day 3	722		-0.1	2.4	3.4	-0.8	14.6	20.4	56.3
RC									
RC day 1	724		0.0	2.0	2.8	-0.1	12.6	17.2	58.4
RC day 1 day 2	724 723	16.2	0.0 -0.3	2.0 2.4	2.8 3.3	-0.1 -2.1	12.6 14.8	17.2 20.5	58.4 56.7
RC day 1 day 2 day 3	724 723 722	16.2	0.0 -0.3 -0.2	2.0 2.4 2.5	2.8 3.3 3.5	-0.1 -2.1 -1.6	12.6 14.8 15.6	17.2 20.5 22.0	58.4 56.7 54.8
RC day 1 day 2 day 3 ZU	724 723 722	16.2	0.0 -0.3 -0.2	2.0 2.4 2.5	2.8 3.3 3.5	-0.1 -2.1 -1.6	12.6 14.8 15.6	17.2 20.5 22.0	58.4 56.7 54.8
RC day 1 day 2 day 3 ZU day 1	724 723 722 724	16.2	0.0 -0.3 -0.2 +0.4	2.02.42.51.8	 2.8 3.3 3.5 2.7 	-0.1 -2.1 -1.6 +2.5	12.6 14.8 15.6 10.8	17.2 20.5 22.0 16.2	58.456.754.861.5
RC day 1 day 2 day 3 ZU day 1 day 2	 724 723 722 724 723 	16.2	0.0 -0.3 -0.2 +0.4 +0.4	 2.0 2.4 2.5 1.8 2.1 	 2.8 3.3 3.5 2.7 3.0 	-0.1 -2.1 -1.6 +2.5 +2.7	12.6 14.8 15.6 10.8 12.5	17.2 20.5 22.0 16.2 18.2	 58.4 56.7 54.8 61.5 60.9
RC day 1 day 2 day 3 ZU day 1 day 2 day 2 day 3	 724 723 722 724 723 722 	16.2	0.0 -0.3 -0.2 +0.4 +0.4 +0.4	 2.0 2.4 2.5 1.8 2.1 2.3 	 2.8 3.3 3.5 2.7 3.0 3.3 	-0.1 -2.1 -1.6 +2.5 +2.7 +2.4	12.6 14.8 15.6 10.8 12.5 13.6	17.2 20.5 22.0 16.2 18.2 19.8	 58.4 56.7 54.8 61.5 60.9 59.3
RC day 1 day 2 day 3 ZU day 1 day 2 day 3 PP	 724 723 722 724 723 722 	16.2 16.8	0.0 -0.3 -0.2 +0.4 +0.4 +0.4	 2.0 2.4 2.5 1.8 2.1 2.3 	 2.8 3.3 3.5 2.7 3.0 3.3 	-0.1 -2.1 -1.6 +2.5 +2.7 +2.4	12.6 14.8 15.6 10.8 12.5 13.6	 17.2 20.5 22.0 16.2 18.2 19.8 	 58.4 56.7 54.8 61.5 60.9 59.3
RC day 1 day 2 day 3 ZU day 1 day 2 day 3 PP day 1	 724 723 722 724 723 722 715 	16.2 16.8	0.0 -0.3 -0.2 +0.4 +0.4 +0.4 -0.3	 2.0 2.4 2.5 1.8 2.1 2.3 2.0 	 2.8 3.3 3.5 2.7 3.0 3.3 2.8 	-0.1 -2.1 -1.6 +2.5 +2.7 +2.4	12.6 14.8 15.6 10.8 12.5 13.6	 17.2 20.5 22.0 16.2 18.2 19.8 16.8 	 58.4 56.7 54.8 61.5 60.9 59.3 54.0
RC day 1 day 2 day 3 ZU day 1 day 2 day 3 PP day 1 day 2 day 3 PP day 1 day 2	 724 723 722 724 723 722 715 714 	16.2 16.8 16.8	0.0 -0.3 -0.2 +0.4 +0.4 +0.4 -0.3 -0.6	 2.0 2.4 2.5 1.8 2.1 2.3 2.0 2.1 	 2.8 3.3 3.5 2.7 3.0 3.3 2.8 3.1 	-0.1 -2.1 -1.6 +2.5 +2.7 +2.4 -1.7 -3.7	12.6 14.8 15.6 10.8 12.5 13.6 12.1 13.0	 17.2 20.5 22.0 16.2 18.2 19.8 16.8 18.5 	 58.4 56.7 54.8 61.5 60.9 59.3 54.0 57.6

Tab. 4: Performance of the ECMWF model averaged over all sites for daily-integrated predictions up to 3 days ahead.

	Mean GHI (MJ/m ²)	MBD (MJ/m ²)	MAD (MJ/m ²)	RMSD (MJ/m ²)	rMBD (%)	rMAD (%)	rRMSD (%)	FS (%)
day 1		pprox 0.0	2.1	2.8	-0.3	11.8	16.6	58.2
day 2	16.9	-0.3	2.3	3.2	-1.4	13.6	19.3	58.0
day 3		-0.3	2.5	3.6	-2.2	14.9	21.3	55.7

The performance of the ECMWF forecast is better at the daily-integrated time scale than at the hourly time resolution, as expected. Not only the MBD, MAD and RMSD are significantly lower, but also the FS is higher. The daily bias of the predictions tends towards underestimation and is low, ranging between +2.7% and -4.5% across sites and forecast horizons, and with a site average between -0.3% (day 1) and -2.2% (day 3), confirming the increasing trend towards underestimation with the forecast horizons. The ECMWF forecast's RMSD has increasing values with increasing days. The rRMSD varies across sites between 15.5% and 17.2% for day 1,

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between 18.2% and 20.2% for day 2 and between 19.8% and 22.5% for day 3. In average terms, the rRMSD of the ECMWF forecast increases from 16.6% at day 1 to 21.3% at day 3. The persistence has higher rRMSD values (ranging from 39.7% to 47.8% for 1 to 3 days ahead, respectively), arising to the high FS values obtained for ECMWF daily forecast, as shown in Tab. 4. Fig. 3 shows the rRMSD trend for the daily integrated values, discriminated by each site (Fig. 3a) and site-averaged (Fig. 3b, which also includes the persistence rRMSD values). There is a slight variability of performance across the sites in the region, as shown by the little difference in the bars of Fig. 3a. The MAD metric averaged between sites presents increasing values from 2.1 MJ/m² for day 1 to 2.5 MJ/m² for day 3, which in percentage correspond respectively to 11.8% and 14.9%.



Fig.3: Performance model daily forecast.

Other studies in other parts of the world, i.e.. Lauret et al. (2016), Remund et al. (2008), Perez et al. (2013) and Lorenz et al. (2009) reported performance evaluations of the daily-integrated ECMWF forecast, with rMAD values ranging from 14% to 32% and rRMSD values ranging from 22% and 45% for 1 to 3 days ahead, respectively. Comparing our results with these studies is not straightforward, as each evaluation has its own particularities. Some varying conditions are the spatial resolution of the model, the climate characteristics at each site, specially its short-term solar irradiance variability caused by unstable sky conditions that are difficult to predict, and the use of temporal interpolation techniques to convert a 3h forecast into a 1h forecast. Likewise, our results are similar and slightly better to those reported in the Perez et al. (2013) for the southern region of Spain, at altitude and latitude similars to that of the Pampa Humeda region, with an rRMSD ranging from 22% to 29% for 1 to 3 days ahead.

Daily-integrated forecasts evaluations of NWPs in our region are presented in Porrini et al. (2017) and Teixeira-Branco et al. (2018), using the GFS-driven WRF up to 3 days ahead as mentioned before. According to Porrini et al., the WRF+GFS strategy showed an average rRMSD ranging from 27% to 39% for 1 to 3 days ahead, respectively. On the other hand, Teixeira-Branco et al. (2018) reported an irradiation overestimation of 22% and rRMSD values ranging from 43% to 51% for the same time horizons and using the same initial and boundary conditions. These differences are explained by the different parameterizations used for the WRF in both works. The ECMWF forecast provides better performance than the previously tested joint use of GFS and WRF, which up to date are the only models evaluated for the region with extended data sets.

4.3 Evaluation of the performance's dependence on sky conditions

In this section we present the ECMWF model's performance for the daily-integrated GHI forecast as a function of daily average sky conditions. This discrimination is achieved by using the daily clearness index (K_T) which is the result of dividing the GHI ground measurements by irradiation incident on a horizontal surface at the top of the atmosphere, as a proxy. The three considered daily conditions are: clear sky (K_T above 0.65), partly cloudy (K_T between 0.65 and 0.35) and cloudy or overcast (K_T below 0.35). These ranges have been determined from visual inspection of the clarity index histograms and are similar to those reported by Fanego et al. (2012). During

the evaluated period the clear sky days represent about 41% of the samples, the partly cloudy days about 38% of the samples and the overcast days around 21% of the samples. The results are presented in Tab. 5 and Fig. 4, averaged across all sites.

As it can be seen from Tab. 5 and Fig. 4, both metrics (MBD and RMSD) increase with the forecast horizon (days ahead) for each sky condition, as expected. For cloudy conditions the forecast model shows important overestimation figures, with rMBD between +38.5% to +41.7%. It is clear that the models underrepresents the occurrence of cloudiness and, in particular, the overcast sky condition is importantly misrepresented. As a consequence, the rRMSD obtained is also very high for this sky condition, being between 68.3-78.4%. It shall be noted that although these relative metrics are high, the absolute indicators are not so notable, being approximately around 2 MJ/m² for MBD and between 3.7-4.2 MJ/m² for RMSD. The model's forecast presents its lower biases under partly cloudy sky conditions. For day 1 it is almost unbiased (MBD \approx 0), and for day 2 and 3 it presents a slight underestimation, around -2%. The rRMSD are intermediate for this sky condition, ranging from 16.1% to 23.6% for day 1 and 3, respectively. The clear sky irradiation is underestimated (rMDB between -5.4% and -7.3%), for instance, the bias is higher than under partly cloudy conditions. By inspecting the data scatterplots for this clear sky evaluation, we have observed that this underestimation is caused by some incorrectly forecasted clouds, i.e. it is not caused by an underrepresentation of the clear sky irradiation. Although the clear sky MBD is not the lowest in these three sets, the RMSD shows its best figures (between 8.5% and 12.4%). This is of course associated with the lower variability of the clear sky data in comparison to cloudy conditions. Fig. 4 illustrates the previous comments based on the absolute metrics.

Forecast horizon	Sky conditions	Mean GHI (MJ/m ²)	MBD (MJ/m ²)	RMSD (MJ/m ²)	rMBD (%)	rRMSD (%)
day 1						
	Clear sky	23.6	-1.2	2.0	-5.4	8.5
	Partly cloudy	16.1	≃0.0	2.9	+0.2	16.1
	Cloudy	5.5	+2.0	3.7	+38.5	68.3
day 2						
	Clear sky	23.6	-1.5	2.6	-6.4	10.9
	Partly cloudy	16.1	-0.3	3.4	-1.8	21.4
	Cloudy	5.5	+2.0	3.9	+37.6	72.2
day 3						
	Clear sky	23.6	-1.7	2.9	-7.3	12.4
	Partly cloudy	16.1	-0.4	3.8	-2.4	23.6
	Cloudy	5.5	+2.2	4.2	+41.7	78.4

Tab. 5: Daily-integrated performance evaluation discriminated by sky condition (using K_T as proxy).



Fig.4: Daily-integrated performance evaluation discriminated by sky condition.

In sum, this work have validated for the Pampa Húmeda region some previous knowledge about the general performance of the ECMWF model for solar irradiation forecast: (i) the model's performance is one of the best of its kind, being to date the best performing NWP in our region (in comparison to the ones that have been previously evaluated with extended controlled-quality data sets), (ii) the model presents some difficulties to forecast the occurrence of clouds, specially for very low clearness index days. The GHI forecast of the ECMWF model varies its bias behavior with the presence or absence of cloudiness, from underestimation under clear sky conditions to overestimation under overcast situations. In spite of these deficiencies, the gains with respect to the previous application of other NWP models in the region are quite significant.

5. Conclusions

A performance evaluation of the GHI predictions provided by the global ECMWF model is presented for the Pampa Húmeda region, using two years of controlled-quality measured data registered at seven sites distributed in the Uruguayan territory. The model's performance assessment is done on an hourly and daily-integrated time scales, and for the second time basis, it also includes a discrimination by different sky conditions based on the daily clearness index. To quantify the forecast uncertainty we employ the most commonly used statistical indicators in the field, namely, the MBD, MAD, RMSD and FS. The evaluation is aimed to provide useful operational information on the ECMWF model's overall performance in the region, characterizing its typical uncertainty and detecting predictions' drawbacks.

By assessing the GHI forecast at individual sites, we found no significant spatial variability on the model's performance, indicating that the model's uncertainty does not have a marked geographical dependence. The predictions clearly outperform the persistence benchmark for all metrics and in both time scales. The hourly performance evaluation indicates that the ECMWF solar forecast has a better performance in the central hours of the day and increasing negative biases towards the end of the day and with increasing forecast horizon. For daily integrated values the predictions have a low underestimating bias (rMBD between zero and approximately -2%) and overall rRMSD between $\approx 17-21\%$, increasing in this range with the forecast horizon (days ahead). A dependence of the model's performance with the average cloudiness of each day is found. An important overestimation bias is observed for cloudy (overcast) conditions. This overestimation can reach +38-42% of rMBD and affects the rest of the performance metrics under this condition. The bias figure is not so high in absolute terms, being of approximately 2 MJ/m², but anyway is the highest of the three sky conditions, due to some incorrectly forecasted clouds.

The performance found for the ECMWF solar forecast is the best observed to date for a NWP in the region, which is consistent with previously reported studies in other regions. Furthermore, this is the first assessment of the solar predictions of this model in the Pampa Húmeda region, which allows us to compare it with other forecasting models, previously evaluated in the region. This work can be complemented with the diagnosis of other global models for solar prediction in the region, in order to identify their weaknesses and strengths, and thus define strategies to reduce the solar prediction uncertainty, which is part of our current work.

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M-01. Passive Solar

Analysis of "Green Building" Indicators in a Residential Area Based on Building Information Model

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Abstract

Abstract: In order to analyze the "green building" indicators such as the lighting environment of a residential district in Zibo, this paper builds a building information model based on the general plan of a residential district and the geometric coordinates and dimensions of the household type. From the perspective of solar energy utilization, it emphatically simulates and analyses the sunshine time, sunshine spacing, shielding and projection, indoor lighting environment of the residential district based on the evaluation index standard of green building. The results show that the illumination hours of the residential quarter are more than 2 hours in cold days, the indoor daylighting coefficient is more than 2%, and the ratio of indoor illumination between 269 Lux and 5380 Lux is more than 75%, which basically meets the evaluation index requirements of green buildings. The research results provide effective methods and approaches for building information model based on point coordinates and geometric dimensions, and provide reference and guidance for optimizing district planning, building optimization design and building green buildings.

Keywords: Building Information Model, Sunshine Time, Solar Energy Utilization, Green Building

1. Introduction

At this stage, high-rise and high-density residential buildings have become the main style of new residential buildings in most cities in China. To some extent, high-rise residential buildings achieve the purpose of saving land and improving the plot ratio of residential areas. However, with the continuous rise of the number of medium and high-rise residential buildings in the city, some potential negative problems gradually appear, especially the sunshine dispute (<u>http://gtj.zibo.gov.cn/art/2021/9/30/art_4030_2168112.html</u>, 2021/9/30).

Building information model (BIM) has become an important tool for the transformation and upgrading of the construction industry. It has economic, intuitive, visual and collaborative advantages in analyzing "green construction" indicators such as sunshine time, sunshine spacing, occlusion and projection, indoor light environment, etc. at present, the application of building information model mainly focuses on pipeline synthesis, collision inspection, building planning There are few applications in other stages such as design.

Based on the published geometric coordinates and dimensions of a residential district in Zibo, this paper constructs a building information model, and focuses on the simulation and analysis of the sunshine time, sunshine spacing, shielding and projection, indoor light environment and so on from the perspective of solar energy utilization and based on the green building evaluation index standard. The research results provide effective methods and approaches for building information model based on point coordinates and geometric dimensions, and provide reference and guidance for optimizing community planning, building optimization design and building green buildings.

2. Method of creating building information model based on general planning drawing and house type drawing

The establishment of BIM model is the basis of solar illumination analysis. According to the complete twodimensional construction drawings, BIM model can be created quickly and accurately. The construction drawings are confidential and may not be fully disclosed, but the overall planning drawings of the construction project must be listed and publicized, and the house type drawings of the residence will also be published before the construction project starts. When it is impossible to obtain two-dimensional construction drawings, building BIM model based on the published general planning drawings and house type drawings has become an effective way of solar illumination analysis. The following will first introduce the methods and approaches of building BIM model based on the disclosed general planning drawing and house type drawing.

2.1 A two-dimensional site layout model is constructed based on the building group point coordinates of the general planning drawing

As shown in Fig.1, it is the two-dimensional general planning and design drawing of a community publicized outside the construction site of a community. The drawing contains the planning red line of the community, some corner coordinates of each building complex, building top elevation, roads, greening and other information. With the help of AutoCAD software, a two-dimensional site layout model can be easily constructed, as shown in Fig.2. The numbers in the Fig.represent the number of buildings in the community.



Fig.1: published general layout



Fig.2: constructed two dimensional model

2.2 Construction of three-dimensional BIM model of standard floor based on two-dimensional house type drawings

As shown in Fig.3, it is the house type diagram of the standard floor of building 34 in the community. The drawing contains the dimensional parameters of the internal and external protective structures of the standard floor of the building, as well as the installation position of doors and windows. With the help of Revit software, it is very convenient to build the BIM model of the standard floor of the building, as shown in Fig.4. In combination with the number of floors of each building in Fig.1, copy and move the standard floor to create the BIM model of the building. The BIM model of building 34 is shown in Fig.5.





Fig.4: BIM model of standard layer

The BIM models of other buildings are constructed according to the above methods, and the BIM model of the whole community can be constructed by placing the constructed BIM model at the corresponding position of the site model shown in Fig.2, as shown in Fig.6.



Fig.6: BIM model of the whole cell

3. Sunlight analysis based on green building evaluation index standard

The main factors affecting solar illumination analysis are geographical location, solar altitude angle, atmospheric transparency, sky cloud amount and altitude. Zibo is located in East China and the middle of Shandong Province, with 35 $^{\circ}$ 55 ' \sim 37 $^{\circ}$ 17 ' N and 117 $^{\circ}$ 32 ' \sim 118 $^{\circ}$ 31 ' E. the average altitude is 34.5 m (Meng, 2016).

3.1 Sunshine hours simulation
The severe cold day is the standard day for calculating the sunshine time stipulated by the state, and it is also the standard day for measuring the indoor daylighting time of residential buildings. If the accumulated daylighting on a cold day is less than 2 hours, you can claim corresponding compensation. If the standard of sunshine on cold days is selected, the effective sunshine time zone is 8:00 to 16:00 local time (Gao, 2014).

The distance between the high-rise residence and all kinds of houses behind shall meet the requirement that the effective sunshine time of the sheltered residence on a cold day shall not be less than 2 hours; In the old area reconstruction project, the new residence shall meet the requirement that the effective sunshine time on a cold day shall not be less than 1 hour. The minimum distance between high-rise residential buildings and various residential buildings behind shall not be less than 30 m (http://www.mohurd.gov.cn/wjfb/201905/t20190530_240717.html, 2019/5/30).

Based on Autodesk Ecotect software, the simulated cold sunlight hours on different ground level in the residential area are shown in Fig.7-Fig.10. It can be seen from the Fig.that the sunshine hours on the ground of the residential area meet the requirements of 2 hours, and with the increase of ground height, the more sunshine hours are received on the plane.



Fig.7: ground sunshine hours on a cold day



Fig. 8: sunshine hours at a distance of 3m from the ground on a cold day



Fig. 9: sunshine hours at a distance of 6m from the ground on a cold day



Fig.10: sunshine hours at 9m from the ground on a cold day

Figures 11-12 show the simulation results of sunshine hours on the south facade of building 34 in the residential community. It can be seen from the Fig.that except for the self shielding at the shape of the south facade, the lighting time in other areas of the south facade of the building exceeds 2 hours, and the longer and more uniform the lighting time with the increase of floor height. This is consistent with the conclusion drawn in figures 7-10.



Fig.11: South elevation lighting analysis building



Fig.12: sunshine hours of south elevation

3.2 Indoor daylighting coefficient and light intensity

Daylighting coefficient refers to the ratio of the illuminance generated by directly or indirectly receiving the sky diffuse light from the assumed and known sky brightness distribution at a point on the indoor reference plane to the sky diffuse light illuminance generated by the sky hemisphere on the outdoor unobstructed horizontal plane at the same time. According to the standard for daylighting design of buildings (http://www.mohurd.gov.cn/wjfb/201509/t20150908_224720.html, 2015/9/8), Zibo area belongs to four areas in China's light climate zoning.

The simulation results of daylighting coefficient and indoor illuminance are shown in Fig. 13-fig. 18. It can be seen from the Figures that the daylighting coefficient and illuminance value near the window are large, and the setting of indoor interior wall has a great impact on the indoor daylighting coefficient and illuminance distribution.



Fig.13: Daylighting coefficient of the first floor



Fig.14: Daylighting coefficient of the first floor (without barrier)



Fig.15: illuminance of the first floor -9a.m.



Fig.16: first floor illumination -9a.m. (without barrier)



Fig.17: illuminance of the first floor -15p.m.



Fig.18: first floor illumination -15p.m. (without barrier)

4. Conclusion

Based on the geometric coordinates and dimensions of a public plot plan and house type, this paper constructs a building information model, and focuses on the simulation and analysis of the sunshine time, sunshine spacing, shielding and projection, indoor light environment and so on from the perspective of solar energy utilization and based on the green building evaluation index standard. The results show that the light hours in the residential area on cold days are more than 2 hours, the indoor daylighting coefficient is more than 2%, and the proportion of indoor illuminance between 269lux and 5380lux is more than 75%, which basically meets the evaluation index requirements of green buildings. The research results provide effective methods and approaches for building information model based on point coordinates and geometric dimensions, and provide reference and guidance for optimizing community planning, building optimization design and building green buildings.

5. Acknowledgments

The research was supported by "Zibo science and technology development plan project (2017kj010054)" and "Zibo school city integration project (2020SNPT0064)".

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L. Wang / SWC 2021 / ISES Conference Proceedings (2021)

Study on A Passive Solar Technique and Its Energy Saving Performance in Rural Houses in Qinghai-Tibetan Plateau

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Abstract

Solar energy is increasing essentially to fortify energy security and mitigate CO₂ emission. China committed itself under the Paris Agreement to reach carbon emission peak by around 2030 and achieve carbon neutral by 2060. Solar techniques in rural houses in Qinghai-Tibetan Plateau (QTP) are expected to be significantly developed under this background. This paper introduces a passive solar technique with aluminum frames and glass structure (AFGS), which is widely adopted by local residents in QTP. Firstly, the background for application of AFGS, including climate, economy and residents' living habit, is introduced. Secondly, the effects of this technique on indoor temperature and heating energy consumption of rural houses were discussed based on EnergyPlus simulation software. Thirdly, the impacts of AFGS on indoor natural ventilation environment were simulated by PHOENICS software. Fourthly, power generation capacity, economic cost and benefits of AFGS replaced by photovoltaic (PV) system were rough calculated, advantages and challenges regarding changing heating methods from coal to PV system were discussed. Finally, energy saving performance of AFGS on rural houses were summarized. Passive solar technique was expected to contribute more to energy conservation and reduction of CO2 emission on rural houses.

Keywords: Qinghai-Tibetan plateau, passive solar technique, rural houses, energy saving, PV system

1. Introduction

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) confirmed that human activities have an important impact on earth's climate change, particularly from energy use perspective, and that further change is inevitable. Adaptation plans need to be systematically considered by decision makers (Y.P. Cai et al., 2010). Due to the close relationship between energy consumption and climate change related to the emission of greenhouse gases, actively respond to the reduce carbon emission is imminent. As the largest national emitter of greenhouse gases, "China committed itself under the Paris Agreement to reach carbon emissions peak by around 2030 and, in the meanwhile, to increase the non-fossil share of its primary energy to 20%" (Y. Qi et al., 2020). More than that, China announced the ambition to be carbon-neutral by 2060 (Y.W. Weng et al., 2021). Low carbon development is not just a task of energy sector, most industries and departments are involved. The construction sector is one of the 3 major sectors of energy consumption (construction, transportation and industry), reducing significantly direct or indirect greenhouse gas emission from the construction sector is an important task to achieve carbon neutral (China Society for Urban Studios, 2021).

Solar energy is the most abundant, inexhaustible and clean source than other renewable energy such as wind, hydro, etc. which can substitute fossil fuels (C. Peng et al.,2011). In one day, the irradiation from the sun on the earth gives about 10,000 times more energy than the daily use from mankind. The challenge is collecting this available energy at a reasonable cost (Bjørn Petter Jelle, 2012). Although solar energy still contributes a small portion to our energy needs, a mass shift to renewable sources of power is tantamount to a healthy future. One of the most remarkable renewable energy technologies is photovoltaics, which products electricity from the sun, without concern for energy supply or environmental harm.

QTP is located in southwest of China and its altitude is between 3000-5000 meters. The region has a typical plateau continental climate, namely low temperature, little precipitation comprises the distinguished features (Y.P. Fang et al., 2002). This region receives the largest amounts of solar radiation in all of China for its high altitude, low moisture and dust content in the atmosphere (Q. Wang and H.N. Qiu, 2009), and annual total radiation amount ranges 4000–

10100 MJ/m2 (Z.R. Zhu et al., 2006) (Fig. 1). The annual sunshine hours in most areas in QTP are more than 2500h. Xining that is located in QTP was selected as a case to study the solar energy utilization of rural houses, and field investigations were carried out. Available time for PV generation of Xining is 1460h (National Energy Administration, 2019).



Fig. 1: Distribution of solar energy in Qinghai Tibetan-Plateau

China has implemented several policy to promote solar energy utilization in QTP. The early plan was Brightness Programme in 1999 to 2000, the plan relied on solar and wind applications to provide electricity to 23 million people located in Gansu, Qinghai, Inner Mongolia, Tibet and Xingjian by 2010, and to provide 100 W of capacity per person (Y.P. Fang, Y.Q. Wei, 2013). In 2007, China's National Climate Change Program was released, it planed to actively developing solar power and solar heating, including popularizing family-use photovoltaic power system; and popularizing household solar water heater, solar greenhouse and solar stove in rural areas (CPGPRC, 2007). In 8th September, 2021. National Energy Administration of China have published the "Notification of the Comprehensive Department of the National Energy Administration on publishing the list of pilot projects for roof distributed photovoltaic development in the whole count" (National Energy Administration, 2021). This project plan was to promote the popularization of PV technology in 676 counties and cities, 41 counties and cities of QTP were in the list. In the near future, there will be more policies to encourage the application of PV technology in buildings.

Most of the builindgs in QTP are rural houses, many residents there still use coal and cow dung as heating energy. PV industry in QTP has made remarkble development, but there are many challenges for promoting PV system into rural houses. What are the challenges and advantages if PV system are adopted in rural houses. Taking Xining as an example, here we introduced a passive solar technique widely used by local residents, then discussed the changes and influence if PV system was used to replace it.

2. Methods

2.1. Investigations in Xining region

There is a thriving PV industry in QTP, mostly centered in Xining. Xining-based PV sales companies have extensive networks for selling, marketing and servicing household PV systems for rural farmers and nomads (S.J. Ling et al., 2002). At present, household PV systems for rural houses in Xining region has constant development, and that is mainly distributed in pastoral area. PV systems are rarely adapted in rural houses in urban area. This is because convenient transportation makes residents use coal as life and heating energy, instead of rely on expensive PV equipment. The investigation showed that about 4 tons of coal (worth \$492) was needed in heating period for each house. The combustion of these fuels results in the emission of large amount of smoke, containing oxides of nitrogen and sulphur, inhalable particulates and carbon monoxide etc., which could pollute indoor air and hazard human health (L. Hua et al., 2016). Clean and cheap heating energy is the common need of local residents.

Weather in Xining is cold in winter and cool in summer (X.L. Wang et al., 2020). Monthly average temperature, monthly average global radiation and direct normal radiation are come from meteorological documents of EnergyPlus (U.S. DOE, 2021). It is generally considered that heating starts when outdoor average temperature is \leq 5 °C last for 10 days. Meteorological data show that monthly average temperature lower than 5 °C are distributed from October to April of next year (Fig. 2). According to this standard, the heating period of rural houses in Xining is about 6 months, from 15th, October to 15th, April, last for 183 days. This heating period has been used for decades (J.H. Zhang et al., 2006).



Fig. 2: Monthly mean temperature and radiation in Qinghai region

The layout of traditional rural houses in Xining generally present the Chinese character "回" (Fig. 3), which are also known as Zhuang-Ke building. The most remarkable feature of Zhuang-Ke building is the enclosed courtyard which can prevent cold wind. Nowadays, contemporary residents use aluminum frames and glass structure (AFGS) to enclose the courtyard instead of brick structure (Fig. 3). New structure can prevent cold wind, accept more sunlight, raise indoor temperature and keep the yard clean. It is popular because low cost, easy construction and good flexibility. Meanwhile, this structure is a low-cost passive solar energy technique. In the field investigation, it can be found that residents have different methods of closing their courtyard to their personal living habits and building characteristics. This paper discusses the energy saving performance of this technique in different enclosure methods. Further study will discuss the advantages and disadvantages of replacing this technique with PV system.



Fig. 3: Traditional rural houses (left) and contemporary rural houses (right) in Xining, Qinghai

2.2. Typical rural house

A contemporary rural house (Fig. 4) widely used was selected as a typical model to discuss the energy saving performance of AFGS in different enclosure methods. This building is 2 floors, building height is about 7.2 m, and floor area is 62.3 m^2 (including 1 living room, 3 bedroom and 1 bathroom). The kitchen is separated from the main building and located in a corner of the courtyard, and the courtyard area including kitchen is 47.4 m². 50mm XPS insulation board is adopted for the external wall and roof. The building plan is shown in Figure 5.



Fig. 4: Typical rural house in Xining region



Fig. 5: Building plan of the typical rural house

2.3. Temperature and energy consumption simulation based on EnergyPlus software

4 main courtyard closure models were established by using Open Studio based on typical rural house. Model 1 did not close the courtyard, which was a reference model. Model 2 to 4 were adopted different way to enclose courtyard, they were experimental models (Fig. 6). Model 2 represents rural houses that do not enclose the entire courtyard, but the outer corridor is closed and large-area windows are opened. Model 3 represents buildings that enclose the courtyard on the 1st floor and outer corridor on the 2nd floor. Model 4 represents rural houses that enclose the entire courtyard with a height of 2 floors. There are more than 4 methods of closure courtyard actually,the most popular methods were selected as examples in this paper.

Indoor temperature of 4 models under non-heating state was simulated to compare the insulation performance of different enclosure methods of AFGS. Meteorological data of Xining region were from the official website of EnergyPlus (U.S. DOE, 2021). The running time of indoor temperature simulation in non-heating state was the whole year. 4 people were set in the building, operating time and efficiency of equipment and lighting were set with reference to the actual situation of local residents. Building envelope of simulation models was referred to the actual construction of rural houses. U factor of exterior wall and roof of models was set as 0.457 W/m²K. U factor of exterior window was set as 2.686 W/m²K, solar heat gain coefficient (SHGC) of glass was set as 0.764. Air change rate was set as 1 time per hour.

Energy consumption of 4 models in heating period were simulated to compare the energy-saving performance of different enclosure methods. The heating temperature was set to 18 °C, and heating was only set for bedrooms and living room. The run period of heating ventilation and air condition (HVAC) was from 15th, October to 15th, April of the next year. Cooling energy consumption in summer was not be considered because residents did not use air condition in summer. The setting of building envelope and air change rate of models were the same as that of non heating simulation.



Fig. 6: 4 rural house models for EnergyPlus simulation

2.4. Ventilation simulation based on PHOENICS software

Indoor ventilation environment can be affected by enclosing the courtyard, local residents set some windows on the AFGS to adjust indoor air environment. The investigation showed that the risk of soot poisoning and allergic rhinitis will be increased for those who living in a poor ventilation house. In order to compared the impact of different

practices on indoor wind environment, PHOENICS software was used to simulate the indoor ventilation environment of 4 models (Fig. 7). The date was set at 2 p.m. on July 15th. Meteorological data of wind and sun were come from EnergyPlus (U.S. DOE, 2021). The simulation interests focused on livingroom's indoor wind speed and air age.



2.5. Comparison of aluminum frames and glass structure and solar PV technique

2021 is the first year for China to achieve the goal of carbon emission peak and carbon neutral. Boosted by impressive technological innovation and cost reductions, photovoltaic (PV) technology is widely used in the QTP as an important way to reduce carbon emissions (Y. Huang et al., 2021). According to relevant research, the cost of distributed PV system in QTP will be \$ 6.2 per 1 kW in 2025(CEPPEI, 2019), low cost of PV system enables it to be popularized in the rural houses in QTP.

This study assumes that in the future, with the incentive of policies, solar PV system is widespread used in rural houses as the only source of energy, and coal was abandoned. Based on the current conversion efficiency of solar PV system, carrying area, energy generation capacity and cost of PV system for 4 rural houses' models were discussed. Purpose of this discussion is to explore the possibility and difficulty of carbon neutral in rural houses in Xining region.

3. Results and discussion

3.1. Indoor temperature of rural houses in natural state

Indoor monthly average temperature of 4 models in natural state were simulated (Fig. 8). Results showed that, 1) indoor monthly mean temperature of 4 models changed synchronously with outdoor temperature without heating. 2) Monthly mean temperature was the highest in July and the lowest in January. 3) Indoor temperature in Model 1 and Model 2 in summer (Jun.-Aug.) was lower than that of the other two models for about 2 °C. 4) The time when monthly indoor temperature was higher than 18 °C was distributed from mid-May to mid-September. 5) The maximum monthly mean temperature of 4 models was lower than 25 °C, therefore, rural house did not need refrigeration in summer. 6) Temperature change trend of 2 floors in 4 models had almost the same trend. 7) Monthly mean temperature of 1st floor was lower than that of 2nd floor from January to July, and high than that of 2nd floor from August to December.



Fig. 8: Indoor monthly mean temperature on the 1st floor (a) and on the 2nd floor (b) of 4 models

15 °C is the cold feeling turning point of human body (J.H. Zhang et al., 2006). Monthly mean temperature is lower than 15 °C of 4 models is distributed from October to April of next year, which is consistent with the heating period

of Xining region. Indoor temperature could be improved by enclosing courtyard with AFGS. But it can not change the heating demands of rural houses. High indoor temperature of enclosed courtyard in model 3 and model 4 may occur in summer according to the field investigation and simulation (Fig. 9). Appropriate cooling measures need to be applied for these practices. Indoor temperature of rooms and enclosed courtyard in model 2 is higher than that of model 3 and model 4 in winter, which means model 2 has better insulation performance than other 2 models.



Fig. 9: Indoor monthly mean temperature of enclosed courtyard of 3 models

3.2. Heating energy consumption and carbon emission in different models

Energy consumption simulation is an important way to compare the energy saving performance of different construction. Simulation result of heating energy consumption from 15th, October to 15th, April was shown in figure 10. Results showed that, 1) Monthly energy consumption of 4 models showed a single peak distribution, which was the highest in January and the lowest in October. 2) When outdoor temperature was lower, heating energy consumption was higher. 3) Annual energy consumption of model 1 was the largest and that of model 2 was the smallest, annual heating energy was model 1 > model 3 > model 4 > model 2.



Fig. 10: Monthly energy consumption (a) and annual energy consumption (b) of 4 models for heating

Outdoor temperature varies the same trend with the solar radiation intensity (Fig. 2), In heating season, when outside environment goes colder, solar radiation intensity goes lower, but heating energy demands become higher. Uneven time distribution of solar energy resource increases the difficulty of utilizing it to reduce heating energy consumption in winter. Annual heating energy consumption can be reduced by enclosing courtyard with AFGS, and model 2 performs best. This is because construction of model 2 is more conductive to using solar energy to raise indoor temperature.

Results from non heating simulation showed that passive solar technique can not change the situation that indoor temperature of rural houses in winter was low and local residents still needed using coal for heating. On the other hand, heating energy consumption can be reduced by improve passive solar technique. In order to achieve the goal of carbon emission peak in residential building, adaptation plans need to be systematically considered by decision maker, and more efficient passive solar techniques needed to be discovered.

3.3 Indoor ventilation environment in different models

Local residents use AFGS to enclose the courtyard is to prevent cold wind, but it will also increase the risk of soot poisoning and allergic rhinitis in winter. According to field investigation and news (QHNEWS, 2011), a large proportion of residents in Xining region suffer from allergic rhinitis, and many people have experienced soot poisoning. Natural ventilation result is shown in figure 11 to figure 13.



Fig. 13: Indoor wind speed value (left) and air age value (right) in summer of living room in 4 models

The test point was located 1.5m high in the middle of the living room on the first floor of 4 models. Ventilation simulation results showed that, 1) Indoor wind speed of living room under natural condition was Model 1 > Model 3 > Model 4 > Model 2, when the indoor wind speed was higher, the air age was lower. 2) When outer windows were opened, indoor ventilation environment at the height of less than 2 m could meet the living demand. 3) Indoor air environment was generally good because the building depth was small.

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Indoor wind environment simulation of enclosed courtyard in summer is based on the ideal condition. In fact, residents can not adjust opening status of window in time in summer, which may cause over high indoor temperature. Indoor ventilation environment is poor in winter, because residents usually close the window to prevent cold wind from outside.

3.4 Comparison of AFGS and solar PV technique

There is general consensus among future energy studies that solar energy will gradually substitute fossil fuels and become the solution to a sustainable energy supply of the world (BP Energy Economic, 2021). In 2021, National Energy Administration of China has selected a number of counties and cities to develop roof distributed PV system as pilot projects. 41 counties and cities of QTP were in the list, and 5 counties of them located in Xining region (National Energy Administration, 2021). The notice required that at least 20% of roof area of rural houses required to installed solar PV system by 2023. In the near future, solar PV system will be widely utilized in rural houses in Xining region. Under this situation, it is necessary to discuss the advantages and challenges of the widespread use of PV systems in rural area. As an application of the PV technology, building-attached photovoltaic (BAPV) systems have attracted an increasing interest in the past decade, and have been shown as a feasible renewable power generation technology to help buildings partially meet their load. BAPV are considered an add-on to the building, not directly related to the structure's functional aspects. They rely on a superstructure that supports conventional framed modules (S.F. Barkaszi, J.P. Dunlop, 2001). This paper assumes BAPV systems will replace the AFGS technique in these 4 models, energy generation capacity and cost of this change are discussed.

Firstly, Surface area of models which PV panels can installed should be estimated. PV panels should be attached on reasonable building surface. Shadowing effect, ambient temperature, the direction of the building and the slope of the PV have a significant effect in order to achieve higher power output and efficiency in the building applications. (Emrah Biyik, 2017). Thus, roof and south exterior wall are ideal installation area for PV panels. For 4 models in this paper, roof and south exterior wall above 2nd floor are ideal area, because the side wall of rural houses is adjacent to other buildings, and there will be shadows of enclosing wall on the south wall in the 1st floor. Building surface area (blue area) of 4 models that can PV panels be install is shown below (Fig. 14). Effective installation area of model 1 is 60 m², that of model 2 is 70.5 m², that of model 3 is 109 m², that of model 4 is 103 m².



Fig. 14: Building surface areas of 4 models that can install PV panels (blue area)

Secondly, power generation capacity of 4 models is estimated. Power generation capacity of stand-alone photovoltaic system is related to effective installation area, total amount solar radiation, conversion efficiency of PV array and comprehensive system efficiency. Annual power generation of PV system can be estimated by the following formula (H.X. Wang, G.Z. Wu, 2012.).

$$E_p = H_A \times S \times \eta \times K \tag{eq. 1}$$

- E_p Annual power generation ((kWh);
- H_A Total annual solar radiation per unit area (kWh / m²);
- S Total area of PV module (m2);
- η Conversion efficiency of PV array (%);
- K Comprehensive system efficiency.

D.K. Hu assessed the solar energy resource of Xining city in nearly 50 Years, the result showed that the total mount of annual solar radiation is 1450 - 1774 kWh / m². 1700 kWh was taken in this paper in order to facilitate the calculation. The output of passivated emitterand rear cell (PREC) in China accounted for 70% of the total output of

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crystal silicon solar cell in 2019. The average conversion efficiency of product of most enterprises has reached about 22% by the end of 2019 (China Photovoltaic Society, 2020). Although conversion efficiency of p-type PREC monocrystalline silicon solar cell of Longi has broken the world record and reached 24.03% in 16th January, 2019, and there will be higher efficient solar cells in the future. This paper use 22% for calculation. Effect of angle for installation photovoltaic arrays on conversion efficiency was not considered in order to simplify the calculation. Comprehensive system efficiency K is related to conversion efficiency of the subassembly and inverter, energy losses coefficient, grid power system efficiency, annual utilization rate of system. Comprehensive system efficiency in this calculation is 0.784 base on consider all factors (X.Y. Ma, Y. Zhao, 2019). Annual power generation of PV system of 4 models can be calculated and the result was shown below (Fig. 15).



Fig. 15: Annual power generation and annual heating energy consumption of 4 models

The results showed that, annual power generation of 4 models were larger than their heating energy consumption. Solar power generation of model 1 and model 2 could cover their heating demands in an ideal condition, but they had weak potential to resist risks. Power generating capacity of model 3 and model 4 was more than twice their heating energy demands, which means these 2 models is more capable to ensure power supply and resist risks. That is, rural houses may achieve carbon-free through appropriate design.

Thirdly, one of the most important issues with solar panels is cost. Solar cells in the early 1950s cost 286 USD/W and reach efficiency of 4.5-6% (J.H. Yong, 2011), with the greatly increased demand and development of industrial technology, the price of PV panels has declined a lot (B. Sun et al., 2021). Based on the current cost of PV system in Xining, economy cost and benefit of PV system were compared.

PV combined with electric heating equipment is a feasible technical solution for rural houses. R.D. Zhang et al. have compared 3 PV methods of clean housing heating including PV + electric heating, PV + air source heat pump and PV + phase change thermal storage for rural area in Xining region. Economic and environment benefits of the 3 methods were analyzed (R.D. Zhou et al., 2020). D.H. Chang et al. did an economic benefit analysis on PV power generation in a poverty alleviation project in rural area of China (D. H. Chang et al., 2020). It could be found that equipment with high electrothermal efficiency had a higher price. This paper discussed economic cost and benefit of utilizing PV systems and passive technique (AFGS + coal heating) on rural houses represented by model 4 based on the research result of relevant studies.

The information of PV systems came from the data combination of relevant studies (R.D. Zhou et al., 2020; E. Gul et al., 2022). The initial cost of PV + equipment system was about 6,000 to 9,000. It is assumed heating for 12 hours a day, heating period is 183 days, the annual heating energy for different heating equipment was distributed from 6,000 to 19,000 kWh. Annual PV power generation of model 4 was calculated above and it was 30,200 kWh. Time of cost back of PV + equipment system in rural houses was about 6 to 8 years.

The cost of AFGS in model 4 was about \$600 according to the local market price. Unit price of high-quality coal is 170.5 per ton, and 4 tons of coal were needed for heating in most rural houses. So that initial cost of AFGS with coal heating is about \$1282. However, an annual additional cost was needed because residents should buy coal for heating every year. According to the field investigation, most of the coal burned by residents in Xining was lignite coal, whose carbon content was about 70%. Most combustion of coal was insufficient because residents used household coal stoves to burn coal, and there was little treatment for the carbon emissions from burning, but emit them into the outdoor. It is estimated that burning a ton of coal produces about 3 tons of carbon dioxide (CO₂) and

burning 4 tons of coal could cause about 12 tons of carbon emission a year. Economy cost and benefits of PV + equipment system and AFGS + coal heating was show in Table 1 (Tab. 1).

Contents	PV + equipment system	AFGS + coal heating	
Initial cost / \$	6,000~9,000	1,282	
Annual additional cost / \$		682	
Annual power generation / kWh	30,200		
Annual heating energy need / kWh	6,000~19,000	1,4581.2	
Annual carbon emission / ton		12	
Time of cost back / year	6~8		

Tab. 1: Economy cost and benefits of PV + equipment system and AFGS + coal heting

There was a higher initial cost for using PV + equipment system than using coal for heating. Although utilization of PV + equipment system can eventually recover the cost by selling electricity to national grid and become a part of residents' income in the useful life (R. M. A. Domingos, F.O. R. Pereira. 2021). It was still a difficult decision for most people in rural area to pay more than 10 times price for a new heating system in a short time. More than that, the problems of degeneration and maintenance of PV panels, lack of knowledge of PV system for residents, inadequate infrastructure etc. are hinder the population of PV system in rural area of Xining region.

There are more than 10 million residents live on the QTP and most of them live in rural houses. Coal is still the main heating and cooking energy for residents at present, family coal combustion across this region is an important source of carbon emission. QTP is considered to be the ideal place for promotion of PV technology for its rich in solar energy resources and cold climate (Y. P. Fang, Y. Q. Wei, 2013). PV system will be adopted widely in rural houses of QTP in the future, which is supported by the carbon neutral commitment of China, national incentive policies and decrease in PV system cost. Fossil fuel will be eliminated because of excessive greenhouse gas emissions, which do not meet the requirement of sustainable development.

4. Conclusions

Residents enclose their courtyard with AFGS can improve thermal insulation performance of rural houses, although this technique is initially intended to prevent cold wind and keep the courtyard clean. Model 2 of 4 models in this paper has the best energy-saving performance because the small sunroom can transfer better the heat of solar energy into living area than a large one. There is an impact on indoor ventilation environment by closing the courtyard, but the indoor air quality of 4 models is good because the depth of building is small. Courtyard ventilation conditions of model 3 and model 4 need to be improved. Heating energy are required if only using passive technology in Xining region. Coal is the main fuel for heating, its burning process will emit greenhouse gases and have negative impact on resident's health.

Fossil fuel can be replaced by PV system for heating in rural houses in Xining region. Model 3 and model 4 can provide a larger installation area for PV panels, so that they have a higher power generation potential if adopt PV system on them. There is a higher initial cost of PV system than using coal, but this cost can be recovered in several years, taking model 4 as an example. Promotion of PV system into rural houses is still subject the resistance from the high cost of system, weak awareness of residents and inadequate infrastructure. Incentive policies from the government and technology upgrading from enterprise for solar PV technique will change this circumstance. Fortunately, rural houses in QTP, which is rich in solar energy, can not only achieve zero carbon emission thorough utilization of PV system, but also increase residents' income by selling electricity to nation grid.

It is an overall trend to develop PV technique on building's surface for reducing carbon emission. Rural houses in QTP are ideal place to implement this technique. But insufficient infrastructure and low awareness of residents for new technology still obstruct the promotion of PV technique. Promotion of the advantages of PV technique, heightening the electricity sales subsidies, perfecting infrastructure construction and providing residents with technical services for installation and maintenance of PV system for free could make local residents accept PV technique better. Residents have built diversified courtyard enclosure methods based on their houses' characteristics and personal habits, which provides a rich reference sample for building integrated photovoltaics (BIPV) form. This also avoids the potential problems of BIPV looked like a cookie-cutter.

There were some limitations in this study. For example, power generation capacity of PV system was estimated by formula instead of comprehensive evaluation. Economic cost and benefit of PV system came from a simple calculation without scientific computing. Hopefully, this paper helps in providing an overview of a new version for passive solar technique and development trend of rural houses in QTP, as well as useful reference for the relevant studies.

5. Acknowledgments

This research is supported by the National Natural Science Foundation of China (52078422), the Shaanxi Provincial Key R&D Program - International Science and Technology Cooperation Program (2020KW-066) and the National Natural Science Foundation of China (51778438).

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Passive Radiative Cooling of Structures with Thick Film Nanocomposites

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Abstract

Passive cooling via state-of-the-art "cool roof" coatings significantly drops roof top temperatures by claiming to reflect nearly all electromagnetic radiation incident upon its surface – the result is significant reductions in electricity consumed for air conditioning. However, passive radiative cooling research reports even greater cooling load reductions and potential energy savings. In addition to "reflective cooling", the surface emits thermal radiation through the earth's atmospheric window to the cold of outer space. A literature review of many experiments demonstrates radiative cooling through numerous fabrication methods and material combinations, yet many methods rely upon expensive equipment for nanoscale precision in a controlled environment for uniform multi-layer thin films or nanostructures. The less complex methods encase dyes or nanoparticles into very thin polymer films not suitable for exposure to harsh environmental conditions or application to many structures. Hence, passive radiative cooling technology is still not cost-effective, scalable, and robust enough to be extensively commercialized like "cool roof" coatings. This paper presents a thick film nanocomposite coating to improve upon cool roof technology utilizing selectively emitting nanoparticles and thick film nanocomposite application methods. The proposed thick film nanocomposite coating load increases during winter weather. A scalable passive radiative cooling coating applied on buildings and other surfaces could significantly reduce global warming by balancing the global heat flux.

Keywords: radiative cooling, thick film, nanocomposite, cool roof, spectrally selective nanoparticles, global warming

1. Introduction

Approximately 25% of all the energy used in the U.S. is for cooling of buildings. Although that percentage is lower for the rest of the world, it is rapidly increasing. Currently the US EPA refers to modern urban areas with populations of more than 1 million people as "heat islands" because annual mean air temperature can be $1-3^{\circ}C$ (1.8–5.4°F) hotter than surrounding rural areas. In the evening, the city can be $12^{\circ}C$ ($22^{\circ}F$) hotter than the countryside. (U.S. Department of Energy 2021 and US Environmental Protection Agency 2021) Heat islands increase peak cooling loads, air conditioning costs, air pollution, greenhouse gas emissions, heat-related illness/mortality, and even water pollution (Oke, 1997). In developed countries, over 50% of urban surface areas are either roofs or paved surfaces; this does not include vehicles or other surfaces facing the sky (Al-Obaidi et al. (2014) and Kolokotsa et al. (2013)). In some locations, roofing systems constitute 70% of a home's total heat gain (IPCC, 2021 and Oke, 1987).

Radiative coolers passively cool terrestrial objects by selectively emitting heat through the earth's atmospheric window to the cold of outer space while reflecting electromagnetic radiation outside the atmospheric window. Surfaces exposed to incoming solar irradiance are prime locations for day and night passive radiative cooling technology. Catalanotti et al. (1975) demonstated that a 12.5 µm thick TEDLAR (polyvinyl–fluoride plastic) film on top of aluminum substrate can passively cool a surface 12 °C below ambient temperature at night. Yet this technology to reduce the "heat island" effect did not progress to a commercially available product due to application and durability limitations.

At the global level, an Intergovernmental Panel on Climate Change (IPCC) report states with high confidence that "Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years...Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5° C and 2° C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO₂) and other greenhouse gas emissions occur in the coming decades" (IPCC, 2021).

Outgoing Longwave Radiation (OLR) is a measure of the amount of energy emitted to space by earth's surface, oceans, and atmosphere. For the Earth to remain at a stable temperature, the amount of longwave radiation streaming from the Earth must be equal to the total amount of absorbed radiation from the Sun Mingke et al. (2015). Unfortunately, a report by Stephens et al. (2012) showed that in 2012, the Earth was absorbing $\sim 1 \text{ W m}^{-2}$ more than it was emitting, leading to an overall warming of the climate.

There are many places on earth where the OLR balance is in the negative range. Some of the biggest heat sinks are situated near the equator with an average OLR of -80 W m⁻² (Lee, 2014). Fortunately, a geoengineering approach to increase radiative heat emission from the Earth to space by covering 1%–2% of the Earth's surface with thermally emissive materials that can radiate ~100 W m⁻² through the atmospheric window may counter global warming by bringing the total heat flux back into balance (Munday, 2019). Covering 2 % of the Earth's surface equates to 10,201,440 km², since the total surface area of Earth is 510,072,000 km². It is preferable to place thermally emissive "radiative" cooling coatings on structural surfaces exposed to the sky, like roof tops due to the added benefit of reduced energy consumption and CO₂ emissions, instead of on land in competition with other primal needs such as agriculture, biodiversity, or decentralized production of energy. It may be theoretically possible to balance the global heat exchanges by emitting more infrared radiation from the earth. Presented in this paper is a possible solution to carry out such an ambitious project.

2. State of Art Review

Daytime radiative cooling is the biggest challenge since 95% of the incoming solar heat flux arrives in the $0.3-2.4 \mu m$ waveband during the day. To attain diurnal cooling of a surface below ambient temperatures a radiative cooling coating must overcome the strong solar radiation with high reflection in $0.3-2.5 \mu m$ wavelength range and high emission in the primary atmospheric window. Achieving daytime radiative cooling is a goal of this research since the greatest benefits, like peak load reduction in buildings, can be realized during this time.

A state-of-the-art review of passive radiative cooling did not find a widely available commercial "radiative cooling" product. However, cool roof coatings are widely available which drop roof top temperatures by high broadband reflectance of incoming solar radiation. The U.S. Department of Energy modeled a 15% reduction in the annual air-conditioning energy use of a single-story building with a cool roof (U.S. Department of Energy, 2021). A modeling study by Lamba et al. (2018) for a passive radiative cooling coating with a cooling power of 100 W m⁻² calculated significantly better cooling load reduction than cool roof coating. The model predicted a passive radiative cooling coating on 50% of a roof's surface would eliminate a Chicago, Illinois single-story building's peak cooling load in July, while amazingly reducing a Miami, Florida building's cooling load by 95% in July and 90% in August.

According to Grand View Research (2020) the largest market share of passive cooling coatings belongs to cool roof coatings whose global market size was estimated to be worth USD 3.59 billion in 2019 – thick film elastomeric coatings account for over 64% of the revenue.

The cool roof coating selected for a side-by-side comparison in this research is the GacoRoof GR1600 Series White (Firestone, 2021) whose safety datasheet composition information is listed in Table 1.

Material	CAS No.	Weight % *	
Dimethyl siloxane, hydroxy-terminated	70131-67-8	30-60%	
Limestone	1317-65-3	30-60%	
Distillates (petroleum), hydrotreated light	64742-47-8	10-30%	
Titanium dioxide (dust)	13463-67-7	7-13%	
Butan-2-one O,O',O"-(methylsilylidyne)trioxime	22984-54-9	1-5%	
Silicon dioxide	7631-86-9	1-5%	
Silica, quartz (dust)	14808-60-7	0.1-1.0%	
Aminopropyltriethoxysilane	919-30-2	0.1-1.0%	
Octamethylcyclotetrasiloxane	556-67-2	0.1-1.0%	

Tab. 1: Composition information of leading cool roof product (GacoRoof GR1600 Series White)

The recommended thickness of cool roof coating examined in this research is 22 mil (558.8 µm). Cool roof coatings contain randomly distributed reflective nano and micro sized particles of varying morphology in an acrylic or silicone binder. This research used similar materials, acrylic paint and siloxane (backbone of silicone), as mediums/binder for thick films. The actual composition of the cool roof coating is proprietary but it is safe to assume the volume fraction of particles is between 38 - 79% which is higher than most randomly distrubuted particles in passive radiative cooling research. A modest amount of spectral selectivity by cool roof coatings was observed in Fig. 3 which can be attributed to some common reflective and somewhat spectrally selective compounds like TiO₂, SiO₂, and CaCO₃ used in radiative cooling as well. The absorbance spectrum for the previously mentioned common coumpounds in Fig. 1 below show where the absorbance peaks are in relation to the atmospheric window (depicted by the rectangular box) in frequency range of 769 cm⁻¹ to 1,250 cm⁻¹ and wavelength range of 8-13 µm. (Wiley, 2021).



Fig. 1: Infrared absorbance peaks of (a) TiO₂, (b) SiO₂, and (c) CaCO₃ in relation to the atmospheric window (depicted with rectangular box)

In Fig. 1, TiO₂, SiO₂, and CaCO₃ show low absorbance accross the infrared spectrum which explains favorable cooling properties, while the most spectrally selective coumpound is SiO₂. Kirchhoff's law states that spectral absorptivity

and spectral emissivity of an object in thermal equilibrium are equal, for every wavelength and direction. Since SiO_2 aborbs more in atmospheric window it stands to reason according to Kirchoff's law that SiO_2 will emit more radiation through the atmospheric window. To improve upon cool roof technology, this research examined nanoparticle-based and thick film "radiative cooling" experimental studies - some are summarized in Tab. 2.

Tab. 2: Experimental studies of nanoparticle-based thick film radiative coolers

Experimental	Cooling Power	Substrate /	Type and size materials	Total	Volume
work	(W m ⁻²);	Binder (matrix)	Binder (matrix) nano(nm)/micro (μm)		Fraction
references	$\Delta T = T - T_{amb}$		in film medium		(%)
Bao et al. (2017)	$\Delta T = -5 $ °C night	Aluminum/	Top layer - rutile TiO ₂	>10 µm	4%
		Double layer acrylic resin	Bottom layer –		
			$SiO_2 + SiC$		
			radius = $0.5 \ \mu m$		
Huang and Ruan	100 W m ⁻² daytime	Aluminum/	Top layer - TiO ₂ spheres	500 µm	4%
(2017)	180 W m ⁻² nighttime	Double layer acrylic resin	Radius = $0.2 \ \mu m$		
			Bottom layer - carbon black		
Zhai, Ma et al. 93 W m ⁻² daytime		Silver substrate	SiO ₂ spheres	50 µm	5%
(2017)		/polymethylpentene (TPX)	radius = 4 μ m		
Gonome et al. $\Delta T = -10 \ ^{\circ}C$ (coated		Black and White Paper/	Copper (II) oxide (CuO)	20-60 µm	3-5%
(2014) paper - paper)		Acrylic	micro-particles		
			0.05, 0.89 and 1.9 µm		
Chae et al. (2021)	$\Delta T = -2.8 \ ^{\circ}C$	Polyethylene terephthalate	Al ₂ O ₃ , SiO ₂ , and Si ₃ N ₄ layers	NP layers	95%
		(PET)/ dipentaerythritol	19, 36, and 56 nm,	were	
		pentahexa-	respectively	2.0 - 2.1 μm	
		acrylate (DPHA)		thick	
Li et al. (2020) 37 W m ⁻²		Polyethylene terephthalate	Rod-shape CaCO ₃ fillers	177, 131,	60%
$\Delta T = -1.7^{\circ}C$		(PET) /acrylic paint	length $\approx 1.9 \ \mu m$ and	and 98 µm	
		_	diameter $\approx 500 \text{ nm}$		

The biggest advantage of a good passive radiative cooling coating is that it can perform both day and night. Huang and Ruan (2017) claimed to achieve a daytime net cooling power of 100 W m⁻² and a nighttime cooling power of 180 W m⁻² with a 500 μ m thick double layer acrylic resin coating embedded with 0.2 μ m radius titanium dioxide particles in the top layer while the bottom layer contained carbon black over an aluminum substrate.

Bao et al. (2017) conducted an experimental study of coating combinations with commonly used radiative cooling compounds. The theoretical predictions of cooling 5 °C below ambient under direct solar radiation and 17 °C below ambient at night were not observed; their best daytime surface temperatures were a few degrees above ambient and at nighttime about 5 °C lower than ambient.

Gonome et al. (2014) placed a CuO coating (black in color) with particle volume fraction of 5% and a thickness of 10 μ m on black paper; instead of comparing to ambient temperature they compared its temperature to non-coated black paper and found the coating was 10 °C cooler.

Another experimental study by Chae et al. (2021) reported 2.8 °C below ambient temperature for a 1:1:1 ratio mixture of Al₂O₃, SiO₂, and Si₃N₄ nanoparticles. This research also used compounds which exhibit strong absorption peaks in or near the atmospheric window and low absorption outside the window.

Recently, researchers Li et al. (2020) applied a 60% concentration of $CaCO_3$ in acrylic paint, without the use of spectrally selective nanoparticles, at a thickness of 177, 131, and 98 μ m for solar reflectance of 95.1%, 93.4%, and 88.9%, respectively. The thicker film provided the highest reflectance. Their spectral analysis reveals good reflection in UV-VIS spectrum but lacking selectivity in infrared spectrum; nevertheless, a surface temperature 1.7°C below ambient during the day was reported.

The research review revealed the need to develop a practical, cost effective, scalable, and robust passive "radiative" cooling coating which reduces heat transfer to surfaces by reflecting a maximum amount of solar radiation (0.3-2.5 μ m wavelength) while strongly emitting within primary atmospheric window (8-13 μ m wavelength) to the deep space.

3. Fabrication of Thick Film Nanocomposite

The objective of our radiative cooling research and development is the design and fabrication of a thick film nanocomposite coating containing spectrally selective nanoparticles with highest absorption in atmospheric window and very low absorption outside the window.

The fabrication concept in this research is akin to microelectronic thick film fabrication only in the sense that it's also an additive process, which entails the application of thicker paste layers and thinner ink layers upon substrate as needed. The layers are added sequentially to the substrate to create a thick film with the desired properties. Another departure is much lower energy for fabrication since high curing temperatures are not required. The resultant performance is dependent upon many factors like substrate properties, nanoparticle properties, medium properties, and climatic conditions.

For this research the thick film's thickness scale can be 1 μ m to ~ 600 μ m consisting of ink and/or paste layers. A thin film's thickness is approximately 1000 times thinner than a 100-micrometer thick film. A thick film will be more robust and have an engineering tolerance to still provide radiative cooling despite variations in film thickness and surface properties.

The simple, cost-effective thick film coating application methods in this research are chemical solution deposition (CSD) and/or spray coating of a paste and ink layers upon a substrate illustrated (not to scale) in Fig. 2.

ļ		000000000000000000000000000000000000000	20/200000000000000000000000000000000000
1	Aerosol spraying of	CSD of particle-solvent	Spray binder layer then
	nanoparticles and	mixture; then spray	adhere particles
	medium mixture	binder layer	
		1	1

Fig. 2: Scalable, cost-effective thick film nanocomposite application methods with side-view drawing of particles and binder on surface Note: not to scale

Combinations of these methods with or without paste layers (not shown in Fig. 2) can provide a novel direction for tailoring spectrally selective radiative cooling thick film nanocomposite coatings for colder climate locations to avoid increased heating loads during winter months.

A medium is the matter electromagnetic radiation travels through to reach nanoparticles. A coating medium not only encapsulates the spectrally selective nanoparticles and fillers, but also functions as a binder to facilitate adhesion of film to a multitude of surfaces. Some mediums/binders add favorable spectral selectivity properties, like acrylic's absorption bands within atmospheric window shown in Figs. 4 & 5, which enhance passive radiative cooling. Spectrally selective nanoparticles are chosen with varying levels of absorption within the atmospheric window and high levels of reflectivity outside the window. The nanoparticles chosen enable tuning of the cooling power of the thick film.

4. Characterization

The thick film nanocomposite was characterized using Ultraviolet – Visible (UV-Vis) spectroscopy, infrared spectroscopy by Fourier Transform Infrared (FTIR), Scanning Electron Microscope (SEM), and performance testing techniques.

The UV-Vis spectroscopy was performed with an Ocean Optics USB-2000 UV-Vis-NIR spectrometer equipped with an enclosed chamber. Tuning film for high reflectance within 0.3-2.4 μ m waveband is essential for daytime radiative cooling due to the strong solar heat flux during the day (Naghshine and Saboonchi, 2018).



Fig. 3: UV-Vis spectrum comparison of cool roof coating (top) and thick film nanocomposite (bottom)

The UV-Vis absorbance spectrum graph in Fig. 3 analyzed two samples on aluminum substrates -- the cool roof coating (top orange line) the radiative cooling thick film nanocomposite (bottom blue line). The strong ultraviolet light absorbance of cool roof coatings is significantly more than thick film nanocomposite and ironically due to white pigments like titanium dioxide (Kolokotsa et al. 2013). Tuning the thick film for lower UV absorbance not only increases cooling power, but also extends the life of the coating and surface beneath, since the higher energy UV radiation can readily degrade many materials.

Since the primary atmospheric window is within the infrared spectrum this research concentrated on infrared spectroscopy to obtain desired spectral selectivity. Infrared spectroscopy was accomplished with a Jasco FTIR-6300 spectrometer and a Pike 30spec specular reflectance attachment with a variable aperture designed for the measurement of thick films held the samples. Maximization of absorption in the atmospheric window (illustrated with rectangular boxes in spectra graphs) in Figs. 1, 4, 5, 6, 8, and 9 is an objective in this research to obtain high radiative cooling levels.



Fig. 4: FTIR absorption spectra of a baseline aluminum plate, two nanoparticle samples (Batch 37) one coated with acrylic binder and another with siloxane binder, and cool roof coating all on aluminum plate substrate

In Fig. 4 the same batch of spectrally selective nanoparticles on aluminum foil produced different infrared spectrums with different mediums. The siloxane acrylic binder increased absorption - a change in nanoparticles with Acrylic binder on aluminum foil improves spectrally selective absorption.



Fig. 5: FTIR absorption spectra of baseline aluminum foil and with selective nanoparticle batches RC 9, RC 10, and RC 16 coated by acrylic binder on the baseline aluminum foil.

Spectrally selective nanoparticles will increase absorption; however, the spectrum shape remains similar to the medium. The varying material properties of the nanoparticle, with the known variable of differing absorption levels in the atmospheric window, produced a range of absorption levels. Experimental results in Figs. 4 and 5 show that the absorption peaks closely follow the spectrum of acrylic medium, however, when the nanoparticles are integrated, there is an increased absorption within the whole spectrum and the more spectrally selective the nanoparticle the more influence it will have in making the nanocomposite film more selective. For example, in Fig. 5 since the RC 10 nanoparticle's spectrum is more selective than the RC 9 and RC 16 nanoparticles that thick film is more selective.

A cool roof coating, with recommended thickness of 22mil (558.8 µm), is regarded as a paste layer thick film with high reflectivity fillers. The fillers in a paste layer can prevent transmission of solar radiation to the substrate and limit heat transfer. If the substrate is not reflective, a reflective bottom layer and/or a reflective and/or selective cover or ink layer is added to obtain radiative cooling. In Fig. 4 the degree of absorption and selectivity vary with the medium used for nanoparticles – here acrylic medium shows selectivity and higher absorption within the atmospheric window.



Fig. 6: FTIR absorption spectra (left) and photograph (right top) thermal images (right bottom) for (a) Paste over aluminum plate substrate (b) Paste with TiO₂ ink layer on top over aluminum plate substrate; red arrows identify increased reflectivity. The thermal images (right) with temperature scale (white is hottest).

A nanocomposite paste in Fig. 6, comprised of SiO particles and spectrally selective nanoparticles was formulated to maximize absorption in the atmospheric window while achieving some degree of selective emittance. The paste layer had an absorption peak of 99.9% within the atmospheric window; while the overall infrared emissivity between 6 to 10 μ m was greater than 99.875%, where less than 0.125% of solar radiation is transmitted to substrate. Despite an absorption level over 99% and an absorption peak in the atmospheric window the paste layer didn't exhibit cooling properties because the absorption outside the window was still too high. Then a TiO₂ ink layer placed over the paste, in Fig. 6b, increased selectivity by reducing absorption outside the atmospheric window (red arrows point out change) on both sides of the atmospheric window. The TiO₂ layer slightly reduced the absorption peak in the window increased cooling was observed in the thermal imagery for an estimated 4°C surface temperature reduction. According to Wiley Spectrabase (2021) TiO₂ has its infrared absorption peak outside the atmospheric window at a wavelength of 20 μ m or frequency of 500 cm⁻¹, suggests a more spectrally selective nanoparticle ink layer on top of the paste might increase selectivity and cooling to a greater degree.

The Scanning Electron Microscope (SEM) analysis of thick film samples were performed by a Hitachi S800 or a Hitachi SU70 SEM. The sample analysis provides insight into the nanoparticle size, morphology, and spacing in the nanocomposite.



Fig. 7: SEM micrographs (a) Surface morphology of CSD of solvent and nanoparticle mixture with spray coated binding layer (b) Surface of 47 µm thick film nanocomposite ink layer shows random dispersion of spectrally selective nanoparticles in siloxane binder (c) Magnification of thick film nanocomposite ink layer's spectrally selective nanoparticles, size range 4-6 µm

The surface of nanocomposite films in Fig. 7 reveal randomly distributed spectrally selective nanoparticles and particles spaced 5-10 µm apart with slight agglomeration. Agglomeration will occur in coatings with randomly dispersed particles in a medium and applied by cost effective means. Because of this larger range of particle sizes and agglomeration absorption and reflectance is enhanced throughout the spectrum also in part because of the spectral selectivity of the materials. Nevertheless, both films exhibited spectrally selective properties, because of the spectral selectivity of the binder and nanoparticles



Fig. 8: Infrared spectrum of spectrally selective nanoparticles: (a) Plates 11, 21, and 24 and (b) Plate 33 in Fig. 9 whose cooling levels exceeded that of cool roof coating.

The spectrally selective nanoparticles in Fig. 8 had varying levels of absorption in the atmospheric window with Fig. 8 having the highest levels. In Fig. 9, thermal imagery using FLIR "forward looking infrared radiometer" infrared

camera and a photograph of plates are shown.



Fig. 9: Photograph of plates (top) and thermal imagery (bottom) with color temperature scale to the right; Coated plates from left to right: (a) Cool roof, (b) Plate 21 (c) Plate 11 (d) Plate 24 (e) Plate 33

Ambient conditions for testing were 29°C, 78% humidity, and wind of 8 mph. The side-by-side comparison of thick film coatings and a cool roof coating on aluminum substrates in Figs. 4, 5, and 9 provide a positive indication that the thick film's cooling power can be significantly higher than cool roof coating. The samples on aluminum plates are cool roof coating (Fig. 9a) – a 440 μ m thick paste layer. Nanoparticle and siloxane mixture sprayed on aluminum substrate for Plate 11(Fig. 9c) - 47 μ m thick w/5% particle #37 and Plate 21(Fig. 9b) - 40 μ m thick w/5% particle #39. A chemical solution deposition of siloxane mixture for Plate 24(Fig. 9d) - 58 μ m thick w/5% particle #10 and application of nanoparticles adhered to acrylic binder surface for Plate 33(Fig. 9e) ~30 μ m thick w/5% particle #44. The lighter color on the bottom on Fig, 9c is feedback from the thermal camera. Siloxane binder on aluminum foil had lower absorption than non-coated aluminum and acrylic without nanoparticles in Fig. 5; and when particles were added to siloxane the resulting spectrum did not have the same amount of selectivity as the acrylic binder in Fig. 4. Nevertheless, the cool roof coating was above ambient temperature while the thick film nanocomposite ink layers whether in siloxane or acrylic paint were still below ambient. Also, this experiment demonstrated the ability to tune the emissivity of the thick film nanocomposite by varying medium and spectrally selective nanoparticles.

5. Conclusion

This research experimentally demonstrated a thick film nanocomposite coating fabricated from spectrally selective nanoparticles in complementary mediums over an aluminum substrate can lower surface temperatures more than a leading cool roof coating over an aluminum substrate. Also, a thick film nanocomposite placed on a building in cold climates can avoid heating load penalties by tuning cooling power with nanoparticles offering less spectral selectivity and absorption in the atmospheric window. The passive cooling by cool roof coatings can be attributed to some common compounds found in radiative cooling as well, but the cooling power is limited by its lack of spectral selectivity. The thick film nanocomposite coating combines cost-effective, scalable, and robust properties of a cool roof coating with a higher spectral selectivity and higher thermal emittance through the atmospheric window to offer an alternative with greater cooling power. Theoretically, if a thick film nanocomposite coating with a cooling power of 100 W m⁻² covered 2% of the earth's surface, approximately 10 million square kilometers, it could emit enough thermal radiation to balance the global heat flux.

6. Acknowledgments

The author, David Young, thankfully acknowledges the support from the Clean Energy Research Center, College of Engineering, University of South Florida, Tampa, FL, USA, Molekule and Florida High Tech Corridor Research Grants, Drummond Carpenter Scholarship, and Geosynthetic Research Institute Fellowship Award.

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M-03. Building Integrated/ Added PV and Solar Thermal Systems

Solar thermal, rear-ventilated façades as heat pump sources in multi-storey buildings

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Abstract

The envelope of multi-storey residential buildings offers an untapped potential for the integration of renewable energy supply systems. Due to their specific assembly, rear-ventilated façades exhibit particularly suitable features in this regard: high design flexibility, modularity, easy installation and maintenance as well as the possibility to hide the systems engineering in the ventilation gap. We analyze solar thermally activated façade claddings made of glass, concrete and metal by means of laboratory tests on single façade modules as well as in-situ experimental tests on large-sized façade prototypes, focusing on thermal performance and reliability. We report very different characteristic values, depending on the specific cladding design and on the approach used for the activation: In case of the metal-façade, the zero-loss efficiency η_0 ranges from 0.39 to 0.71 and the heat-loss-coefficient ranges from 6.65 to 14.55 W m⁻² K⁻¹ under laboratory conditions. For the large-scale outdoor façade we determined a zero-loss efficiency of 0.6 and heat-loss-coefficient of 11.24. Based on these results, the potential of the façades as sources for ground-coupled heat pumps is assessed by building simulations with the software TRNSYS for different configurations of the heat supply system. The solar façade reduces the load on the borehole heat exchangers up to 50% and enables a smaller dimensioning of the field.

Keywords: Rear-ventilated façades, solar thermal collectors, TRNSYS, multifamily buildings, heat pump, building envelop, thermal activation, building integration

1. Introduction

In order to reduce carbon-dioxide emissions and achieve a climate neutral energy and heat supply in the building sector, a much greater use of renewable energies as well as the development and the implementation of novel concepts for renewable heat generation in multi-storey buildings are required. For this purpose, European and national directives are tightening the requirements for existing and new buildings focusing on higher renovation rates and on a more effective substitution of fossil fuels. Solar thermal energy and heat pumps can significantly contribute to the heat supply of buildings. While both technologies are becoming more and more common in single-family houses, the technical implementation in multi-storey residential buildings is difficult due to the limited space available both for collectors and heat pump sources.

The integration of solar thermal components in the building envelope offers untapped potential for new solutions with high architectural quality. Rear-ventilated façades are particularly suitable for the solar-thermal activation due to various reasons: The modular design of rear-ventilated façades enables prefabrication and an uncomplicated installation of the activated façade elements. Furthermore, the rear-ventilation gap offers the possibility to hide the systems components (tubing, heat exchangers, etc.). Finally, the wide range of available cladding materials allows the realization of different solutions with a high design flexibility.

A stated goal of the project is to support or replace conventional heat pump sources and thus accelerate the energyoriented refurbishment of urban areas. Conventional heat sources like borehole or air heat exchangers do need appropriate space outside the building. These additional heat sources can be reduced or replaced, if building envelopes can actively contribute to the energy production.

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2. Façade concepts

The basic assembly of a rear-ventilated façade as shown in Fig. 1 consist of the external wall, the façade cladding and a substructure, which builds the static link between the wall and the cladding elements. The substructure is usually built up by wall brackets, which are attached to the anchoring base with a thermal separation, as well as vertically or horizontally running supporting profiles, which hold the façade claddings via visible or hidden fastening elements (FVHF, 2018). The separation between the cladding and the building insulation creates a ventilation gap, which has positive effects on the building's humidity and indoor climate and is the essential characteristic of a rear-ventilated façade. Solar irradiation on the cladding elements creates a natural convection inside the ventilation gap, which drains moisture from the building's insulation. To ensure a sufficient air flow, the depth of the rear-ventilation gap is required to be at least 20 mm with inlet and outlet openings with a cross-section of at least 50 cm² per meter wall length (DIN, 2010).



Fig. 1: Left: Investigated concepts for the solar-thermal activation of rear-ventilated façades. The thermal activation is achieved by implementing different types of heat-exchangers to façade claddings out of concrete, glass and metal. Right: Basic scheme of a rear-ventilated façade

The main development approach for the solar-thermal activation in this project is to apply heat-exchangers to the façade cladding elements and utilize them as solar-absorbers, without modifying the existing façade systems, so that the original appearance of the non-activated façade remains unchanged. For this purpose, we study three different façade systems with cladding elements made of concrete, glass and metal. A main challenge in this regard is to ensure a durable connection with a good thermal contact between cladding elements and heat-exchangers. Fig. 1 shows the concept for the solar-thermal activation for each material.

The development of the solar-thermal activated glass-façade is based on the results of previous research work at the ISFH (Kirchner et al., 2017). Two different types of glasses are analyzed as cladding elements as shown in Fig. 1: Single glazed enameled glass panels and enameled insulation glasses. In both cases the solar irradiation is absorbed in the enamel layer and converted into heat. The generated heat is transferred to the fluid by means of heat-exchangers placed on the rear side of the glass. The heat-exchangers consist of a D-shaped copper tubing and are applied to the glass with heat conducting plates and an adhesive bonding (SolMetall, 2017). The D-shape of the tubing allows heat conduction over a large part of the tubing surface. The heat losses due to long wave irradiation can be reduced by means of a low-emitting layer on the front side of the glass. In case of the insulation glasses the heat-losses are further reduced by introducing an additional front pane separated from the absorber glass panel with a hermetically sealed air or inert gas gap. That way it is possible to generate heat at higher temperatures and, for example, enable direct solar domestic water heating.

For the solar-thermal active metal façade, we investigate cladding elements out of aluminum due to its high thermal conductivity. The connection between heat exchangers and cladding elements is in this case realized either by means of an adhesive bonding or by a form-fitting connection with welded threaded bolts and nuts. In addition to the concept used for the glass façade, we analyze a geometry, with the copper tubing attached to clamp-profiles

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as shown in Fig. 1. This method is commonly used by the façade manufacturers involved in the project for the connection of the cladding elements to the substructure. By applying the same fixing approach for the heat-exchanger as well, process steps during the production and correspondent costs can be reduced. Furthermore, a higher sustainability as well as an easier building approval procedure can be achieved by avoiding the use of an adhesive bonding for the building envelope. By combining the form-fitting connection with clamp-profiles as heat exchangers we expect a better thermal connection than with heat-conducting plates due to the higher thickness of the clamp profiles.

For the thermal activation of the concrete façade so-called capillary tube mats made of polypropylene (PP-R) are embedded directly into the concrete slab. The capillary tube mats consist of a series of plastic tubes with an inner diameter of 2.7 mm placed at a distance of 20 mm to each other. The tubes are connected with manifolds with an inner diameter of 20 mm, creating a parallel connection of the capillary tubes. The impact on the thermal efficiency of the position of the capillary tube mat inside the concrete slab as well as different coatings are analyzed in the project. Another investigation topic is the effect of the activation and of the correspondent operation conditions on the hygrothermal behavior of the concrete cladding.

3. Laboratory tests

For the analysis and optimization of the thermal efficiency of the solar-thermal active metal façade various laboratory tests on different prototypes have been carried out. In the first step we characterized the optical properties of different surface coatings by measuring the reflectance from the ultraviolet to the infrared-range of the electromagnetic spectrum (250 nm to 17 μ m wavelength) on small-scaled cladding samples by using two different spectrometers both equipped with integrating spheres (Cary 5000 from Varian/Agilent Technologies[®] and FTIR Equinox from Bruker[®]). Tab. 1 shows the determined solar absorptance and thermal emittance for a selection of common surface coatings, calculated according to ISO 9050 (absorptance) and Planck's radiation law (thermal emittance) at a temperature of 373 K.

Colour	RAL-tone	Solar absorptance (±0.01)	Thermal emittance (±0.02)
Jet black	RAL 9005	0.95	0.94
Graphite black	RAL 9011	0.95	0.95
Clay brown	RAL 8003	0.82	0.92
Iron grey	RAL 7011	0.89	0.96
Anthracite grey	RAL 7016	0.92	0.96
Silver grey	RAL 7001	0.72	0.94
Blue grey	RAL 7031	0.86	0.95
Emerald green	RAL 6001	0.76	0.93
Gentian blue	RAL 5010	0.75	0.90
Brilliant blue	RAL 5007	0.81	0.94
Red orange	RAL 2001	0.57	0.93
Flame red	RAL 3000	0.63	0.92
Ruby red	RAL 3003	0.66	0.92
White aluminium	RAL 9006	0.58	0.90
Pearl dark grey	RAL 9023	0.81	0.94
Cream	RAL 9001	0.27	0.92
Light ivory	RAL 1015	0.35	0.92

Tab. 1: Determined solar absorptance and thermal emittance of common surface coatings for metal-façade claddings

For the analysis of the thermal efficiency of the activated metal façades several prototypes with a cladding element size of 2250x1166 mm² have been manufactured. For the surface coating we chose the RAL-tone 7016 with a solar absorptance of 0.92 and thermal emittance of 0.96. The prototypes differ in the geometry of the heat-exchanger (Type 1: heat-conducting plates, Type 2: clamp-profiles) and the fixing method to the cladding element as described in section 2. Furthermore we varied the number of tubes and the distance between the pipes (80 mm, 100 mm and 150 mm) of the heat exchanger. At last, we also modified the number of threaded bolts, to study the impact on the heat conduction of the contacted area.

The collector efficiency measurements have been carried out in a sun simulator according to the standard testing procedure (DIN EN, 2018) and the correspondent efficiency coefficients for uncovered assembly based on eq. 1 have been determined. The tests have been performed both with a closed and an opened rear-ventilation gap (depth of the gap: 45 mm), so that a higher air flow on the rear side of the modules due to the artificial ventilation is achieved in the latter case. Tab. 2 shows the results of the performance measurements.

$$\eta = \eta_0 \cdot (1 - b_u \cdot v) - (b_1 + b_2 \cdot v) \cdot \frac{\Delta T}{E_n}$$
 (eq. 1)

Module variant	Ventilation gap	η ₀ [-]	$\mathbf{b_1} [\mathrm{W} \mathrm{m}^{-2} \mathrm{K}^{-1}]$	b ₂ [J m ⁻³ K ⁻¹]	${f b}_{{f U}} [s m^{-1}]$
Type 1, adhesive bonding, 80 mm pipe-distance	Open	0.70	14.55	2.80	0.075
	Closed	0.71	12.88	1.75	0.061
Type 1, adhesive bonding, 100 mm	Open	0,67	13,95	2,7	0,077
pipe-distance	Closed	0,67	11,41	1,48	0,057
Type 1, adhesive bonding, 150 mm	Open	0,58	11,25	1,86	0,096
pipe distance	Closed	0,59	9,90	1,12	0,072
Type 1, form-fitting bonding, 80 mm pipe distance	Open	0.54	11.66	1.91	0.101
	Closed	0.54	9.44	0.92	0.079
Type 1, form-fitting bonding, 100 mm	Open	0,49	10,27	2,17	0,086
pipe distance	Closed	0,50	8,89	1,64	0,071
Type 1, form-fitting bonding, 150 mm	Open	0,41	8,47	1,18	0,120
pipe distance	Closed	0,39	6,65	0,62	0,091
Type 2, form-fitting bonding, 100 mm pipe distance	Open	0,58	11,74	1,66	0,109
	Closed	0,56	9,86	1,22	0,069
Type 2, form-fitting bonding, 100 mm	Open	-	-	-	-
pipe distance, increased bolt number	Closed	0.59	10.39	1.04	0.082
Type 2, form-fitting bonding, 100 mm	Open	0.54	11.70	1.66	0.111
pipe distance, reduced bolt number	Closed	0.54	10.17	0.99	0.044

Tab. 2: Results of the efficiency measurements for prototypes of solar-thermal active metal-façade claddings.

As expected, the module with heat-conducting plates and an adhesive bonding report the highest performance with zero-loss collector efficiencies varying from 71% to 58%, depending on the pipe-distance. On the contrary, the zero-loss efficiency of the variant with heat-conducting plates and a form-fitting connection reaches a maximum of 54% for the module with a pipe-distance of 80 mm and about 50% with a pipe-distance of 100 mm. Comparing the results of the different examined heat exchanger geometries, the variant with clamp profiles reaches higher efficiencies than the variant with heat conducting plates and a form-fitting connection, due to the more homogenous contacted area to the cladding elements. The basic design with 80 threaded bolts per module

reaches a zero-loss efficiency about 56% with a closed ventilation gap. The variation of the bolt number showed little impact on the performance results: Increasing the bolts to 110 units per module improved the zero-loss efficiency to about 59%, while reducing the bolts to 40 units per module reduced it to 54%. The heat loss coefficients showed values comparable to standard uncovered collectors ranging from 6.65 to 14.55 W m⁻² K⁻¹.

4. Outdoor tests

On the basis of the laboratory tests on the activated metal claddings a module design was selected and a largescale thermally activated metal façade was installed on an outdoor test wall, to study the thermal behavior of the façade under real weather conditions. Fig. 2 shows a schematic of the components of the test wall.



Fig. 2: Schematic of the outdoor test wall components. Inlet-temperature and fluid mass-flow are controlled by a hydraulic unit. The room-temperature is emulated via an electrical rear side heating.

The test wall features hydraulic modules for two separate fluid-circuits, enabling the parallel operation of two activated façades. The hydraulic modules allow an operation of the façades with controlled inlet temperatures down to -15 °C and controlled mass flow up to 1600 kg h⁻¹. The controlled fluid temperature is provided by a cooling unit consisting of a water chiller and a 1000 l fluid tank. To emulate the room temperature on the interior side of the wall, surface heating panels have been mounted to the wall's rear side. The heating panels consist of aluminum sheets with attached wires. By controlling the electrical power through the heating wire, a homogenous temperature of about 19 °C on the wall's rear side can be achieved. To reduce temperature fluctuations and heat losses to the environment an additional insulation (16 cm) has been installed on the aluminum sheet.



Fig. 3: Left: Layout of the large-scale solar-thermal activated metal façade. Right: Metal-test façade on the outdoor test wall

The installed metal façade features ten identical active cladding elements each with an area of $2250x1166 \text{ mm}^2$ and an anthracite grey surface coating (RAL-tone 7016, $\alpha = 0.92$, $\varepsilon = 0.96$). The total area of the activated façade amounts to 26.23 m². The façade was installed with a distance of 60 mm between cladding and insulation (mineral wool, thickness: 18 cm, thermal conductivity: 0.035 W m⁻¹ K⁻¹). For the solar-thermal activation we chose the

heat exchanger concept with clamp-profiles, a pipe-distance of 100 mm and a form-fitting connection with 80 threaded bolts per module as described in chapter 2 and examined in chapter 3. The hydraulic connection of the active façade elements to the fluid circuit is achieved by means of four manifolds placed in the middle of the façade, so that a parallel flow through all elements is realized. The connection to the manifolds is achieved by using flexible tubes with hydraulic plug-in connectors. In addition to the active elements a small area (2.33 m²) with standard, non-active cladding elements has been installed as reference. The complete layout of the installed metal façade is shown in Fig. 3.

The investigations on the large-scale active metal façade requires the measurement of various physical values. Fig. 4 gives an overview of the installed measurement equipment. For the analysis of the solar-thermal efficiency various meteorological data are recorded, including several radiation quantities in the façade plane like the hemispherical solar irradiance via a pyranometer, the longwave irradiance via a pyrgeometer and the diffuse irradiance via a pyranometer with shadow ring. Other measured quantities are the wind speed in the façade plane, the relative humidity and the temperature of the ambient air. To investigate the thermal behavior inside the rearventilation gap additional sensors were installed: several PT-100 temperature sensors to record the surface temperature on the cladding elements, two flow sensors to measure the velocity of the air flow, two combined sensors for the measurement of the air humidity and temperature and two special CHM-sensors developed at the Fraunhofer-Institute for Building Physics to directly determine the heat-transfer coefficient on the cladding element, the heat flow from the ventilation gap to the façade and vice versa can be determined. Furthermore, a heat flow plate was installed on the wall to analyze the impact of the solar-thermal activation on the heat transfer mechanisms through the wall.



Fig. 4: Schematic of the measured physical values on the large-scale solar-thermal activated metal façade

In the first step a stationary performance evaluation of the active façade based on the test procedure described in (DIN EN, 2018) was carried out. For the tests the façade was operated with a fluid mass flow rate of 1600 kg h⁻¹ to ensure turbulent flow during the entire testing period. The fluid inlet temperature was frequently varied over the period of several weeks to record data with a high variety of temperature differences. The resulting collector efficiency coefficients for uncovered collectors based on eq. 1 are shown in Tab. 3. Fig. 5 shows a comparison between the efficiency curves determined by means of the laboratory tests and the test under real weather conditions at an irradiance of 800 W m⁻² and wind speed of 0.3 m s⁻¹. With a zero-loss efficiency of about 60% the large-scale activated façade reaches slightly higher performance values than the single module under laboratory conditions, both with an open and closed ventilation gap. The thermal performance at higher temperatures are comparable to the results of the single module measurement with a closed ventilation gap, due to the low flow-rates on the rear side of the large-scale façade modules compared to the flow rates during the

laboratory measurement with an open ventilation gap. The wind-dependency of the heat loss coefficient b_2 and of the zero-loss efficiency b_U are significantly lower for the large-scale façade than the laboratory results in both cases. The deviations result from the low variation in wind speed and generally low wind velocities recorded during the measurement period of the outdoor façade as well as from the different turbulence conditions occurring in the laboratory tests.

Testing conditions	η ₀ [-]	$\mathbf{b_1} [W m^{-2} K^{-1}]$	b ₂ [J m ⁻³ K ⁻¹]	${f b}_{{f U}} [s m^{-1}]$
Outdoor	0.60	11.24	0.84	0.024
Sun-simulator, open ventilation gap	0,58	11,74	1,66	0,109
Sun-simulator, closed ventilation gap	0,56	9,86	1,22	0,069

Tab. 3: Comparison between determined collector efficiency coefficients for indoor and outdoor measurements



Fig. 5: Comparison between collector efficiency curves of the active metal façade determined by means of the laboratory tests and under real weather conditions for a wind speed of 0.3 m s^{-1}

5. System Simulation

To evaluate the behavior of the different façade concepts described in section 2 within a heat supply system, TRNSYS-simulations (Klein, 2014) of a multi-storey building were used.



Fig. 6: Multi-storey residential building featuring 8 flats on 4 floors each with 84 m² living space
The freestanding building consist of 4 floors, each of them featuring 2 flats with 84 m² living space. The south and north façade are equipped with windows Fig. 6. The structural and heating system are chosen according to the current standards for buildings, the boundary conditions assumed for the simulation are stated in Tab. 4.

Weather data	DWD weather data (BBSR, 2017), mean year of present-day test reference year based on the measurement and observation data 1995 to 2012 ("TRY2015 Jahr") for coordinates 48.8975°, 08.7083° (Pforzheim, Germany)
Building	Freestanding multi-storey building with basement, orientation south with a deviation of 13° to east, 672 m ² living space, usable area of 1024 m ² , Type 56
Heat demand / useful heat	34,170 kWh (space heating and tap water)
Demand space heating	23,110 kWh (34.4 kWh/m ²), floor heating Type 362 (S. Holst, 2010)
Demand hot tap water	11,060 kWh (70 - 112 l/d per flat, 45 °C set temperature)(Braas et al., 2020)
Heat generation	37,400 kWh (heat loss buffer storage 1700 kWh)
Buffer storage	1,000 l, 1.8 m high, heat loss 5 W/K
Thermally activated façades	Different cladding materials (concrete, metal, glass) and different areas
Heat pump	Modulating brine-water heat pump; Performance values: COP B0/W35: 4.7 (35%) 4.17 (65%) 3.9 (75%) COP B5/W35: 5.4 (35%) 4.6 (65%) 4.3 (75%); sources: solar façade and borehole heat exchanger; sinks: buffer storage stratified loading of two sections,
Borehole heat exchanger (BHE)	Field of 3 probes with a length of 75 m and a spacing of 6 m

Tal	b. 4:	Boundary	parameters	used for	the	TRNSYS-simulation
			F			

The difference between generated and useful heat originates from the heat losses of buffer storage, riser pipes and decentral instantaneous water heater (IWH). These losses are internal building gains. The simulation is carried out with weather data from Germany's National Meteorological Service, the Deutscher Wetterdienst (DWD) (BBSR, 2017).

The system consists of thermally activated façades, a brine-water-heat pump, borehole heat exchanger, a hydraulic switch, a buffer storage, riser pipes, a decentral instantaneous water heater in each flat, a floor heating system (flow and return temperature 35/32 °C) and single-room air handling unit with heat recovery in each room except corridor, and external shading devices on all windows. The system configurations can be related to the generic system classifications shown in Fig. 7 equivalent to the representation of the energy flows of IEA SHC Task 44 (Frank et al., 2010).

The thermally activated façade serves both as a solar collector and environmental heat exchanger. It not only enables the regeneration of the ground but can also be used as a direct source for the heat pump. Additionally to the borehole heat exchangers, the heat pump loads a buffer tank (Fig. 7). Because of different mass flow occurring in façade, borehole heat exchanger and evaporator of the heat pump, a hydraulic switch is used to connect the three units.

This centralized storage enables the use of decentral instantaneous water heater (IWH) in each flat for domestic hot water heating as required. The floor heating system is controlled to keep the set temperature. Because of the IWH the supply temperature is set all year to 35 $^{\circ}$ C. A schematic of the system is shown in Fig. 8.

Shading device and air handling unit are used as overheating and glare protection.



Fig. 7: Schematic of energy and material flows (green: environmental energy, orange: energy conversion, blue: thermal storage, red: useful energy).

Fig. 8: Schematic diagram of the heat supply system under investigation

The operation of the solar façade as an additional heat source for the heat pump can significantly reduce the load on the borehole heat exchanger. Furthermore, regeneration mitigates short- and longtime temperature reduction of the ground and enables a sustainable operation of the system. As a result, a smaller BHE field, e.g. lower depth, less numbers or reduced spacing of the probes is possible. In this simulation, the reduction is about 25 %. Higher reductions up to 50% can be achieved depending on the operating conditions. The lower the set temperature the higher the performance of the façade but also the risks resulting from surface condensation and freezing as well as the impact on aesthetics and acceptance.

In this simulation, the min. allowed inlet temperature in the façade elements is set to -1 °C. The façade is operated as a heat source for the heat pump if the façade outlet temperature reaches temperatures above 8 K over evaporator outlet. This operation mode stops, if the temperature difference drops below 4 K. This mode is prioritized, to reduce the load of the borehole heat exchangers. In a second operation mode the façade is used to regenerate the ground and thus to enable a smaller dimensioning of the field. Regeneration takes place if the façade outlet temperature is at least 5 K over the outlet and stops as soon as the difference drops below 3 K.

The façade is modelled with the TRNSYS Type 832 (Haller et al., 2013), main collector parameters are shown in Tab. 5 and gained and validated from experimental measurements. The model was validated with measured values. Deviating from Tab. 3, the metal façade has different parameters, since not all measured values were available at the beginning of the simulation.

Symbol	ηο	a 1	a 2	Cwhl	CIR	Ceff	Cwf
Quantity	zero loss efficiency	Linear heat loss coefficient	Quadratic heat loss coefficient	Wind speed dependency of heat losses	Infrared radiation dependency of collector	Effective heat capacity	Wind speed dependency of the zero loss efficiency
Unit	-	W m ⁻² K ⁻¹	$W m^{-2} K^{-2}$	J m ⁻³ K ⁻¹	-	J m ⁻² K ⁻¹	s m ⁻¹
Concrete	0.400	11.3028	-	4.04	-0.2125	282000	0.05192
Glass	0.774	9.3300	-	3.74	0	11000	0.029
Metal	0.602	11.3600	-	0.71	-0.628	14000	0.024
Glazed collector	0.775	5.11	0.0140	0	0	11000	0.14

Tab. 5: Collector parameters of Type 832 for the selected facad	des
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In Fig. 9, the impact of different façade claddings are shown. For this 48 m² south, 33 m² east and 13 m² west façade are thermally activated.



Fig. 9: Simulation results, left: heat flow of façade to geothermal probe for regeneration (SOL->BHE), façade as heat source for heat pump (SOL->HP) and geothermal probe as source for heat pump (BHE->HP); right: energy weighted inlet and outlet temperature of façade

Façades with higher efficiency could reach higher yields. Therefore in the simulation shown in Fig. 9 the use of the façade as a heat pump source is prioritized. At the same time higher temperature of the façade has to be usable to achieve higher system performance. In the investigated configuration the evaporator of heat pump as well as the inlet temperature of geothermal probes represent a limitation for the operating range of the active facade. In further work the potential of using heat from the façade to directly load the buffer storage has to be analyzed.



Simulation results with the concrete façade for different orientation and area are shown in Fig. 10.

Fig. 10: Impact of area and orientation of concrete façade

The façade is used both as an environmental heat exchanger and as solar absorber, the highest yields are achieved on the south side, followed by west and east. A façade area of 25 m², e.g. south, supplies nearly 50% of total energy demand of the heat pump and actively regenerate the geothermal probes to 90 %.

6. Acknowledgments

The work is based on the results of the project "Solar-VHF", funded by the Lower Saxony Ministry of Science and Culture and by the German Federal Ministry of Economy and Energy (BMWi, reference number 03ETW013A-I), following a decision of the German Parliament. The investigations are carried out in cooperation with the Fraunhofer-Institut für Bauphysik and the German companies Konvortec GmbH & Co. KG, Systea Pohl GmbH, Gundlach GmbH & Co. KG Wohnungsunternehmen, , Pforzheimer Bau und Grund GmbH and Clina Heiz- und Kühlelemente GmbH. The authors are grateful for the support and responsible for the content of the publication.

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Profiled Glass Solar Façade with Integrated Heat Pipe Absorber – Experimental Evaluation of Prototypes

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Abstract

The paper presents the development of a solar thermally activated U-shaped profiled glass mainly intended for the use in façades of non-residential buildings. The activation is achieved by inserting a metallic tube-and-sheet solar absorber provided with heat pipes into the air gap of a double-shell profiled glass. We manufacture specimen with different design and size and investigate their performance and thermal behavior by means of indoor and outdoor experiments. For 2 m² modules we report zero-loss efficiencies η_0 up to 0.59 and heat loss coefficients a_1 between 3.8 and 5.8 Wm⁻²K⁻¹ as well as a_2 between 0.012 and 0.03 Wm⁻²K⁻². To analyze thermal comfort issues a small demonstration plant was installed in the south façade of a production hall consisting of profiled glass and was monitored under stagnation conditions over a period of one year. The maximum surface temperatures recorded on the room-side of the module are usually higher than those of standard non-activated glass in winter, but comparable in summer.

Keywords: Building integration, solar thermal collector, heat pipes, profiled glass

1. Introduction

Achieving the ambitious European climate policy goals requires the exclusive construction of nearly zero-energy buildings, significantly higher renovation rates and a much greater use of renewable energies to cover the heat demand (EU, 2021).

The use of solar energy for space heating, domestic hot water and the supply of industrial processes offers a concrete possibility to meet these requirements. Previous approaches are mainly limited to the residential sector and are based on the installation of solar thermal collectors on the roofs of buildings according to the additive principle (rarely on façades). This usually leads to low architectural acceptance and high costs, which has impaired a successful diffusion in the building practice so far (Cappel et al., 2014; Mauer et al., 2020).

An alternative approach to counteract this problem is the solar thermal activation of existing components of the building envelope by modifying and adapting their structure. This approach can enable cost reductions through synergy effects, as materials for mounting systems as well as for building claddings can be saved. In addition, a high degree of design freedom and high-quality architecture can be achieved. So far, different R&D works have been carried out on this topic in the last years (Giovannetti et al., 2016; Mauer et al., 2017; Denz P.-R. et al, 2018; Weiland et al., 2019; Frick et al. 2021), but such products are still hardly available on the market. The known solutions are either too complex or have very high investment costs. There is an urgent need for new architectural and technical building concepts and products that can extend the range of available options for architects, planners and builders in both new and existing residential and non-residential buildings.

In the "Solar Profil" project presented here, we evaluate a new approach in cooperation with the companies Flachglas Sachsen GmbH and Eilenburger Fenstertechnik GmbH.

Aim of the project is the development of a façade system consisting of profiled glass with integrated solar absorber, for the active use of solar energy for heat generation (space heating, domestic hot water or supply of industrial processes).

By combining solar absorbers and profiled glass of different types, the best compromise between energy generation, visual / thermal comfort, aesthetics and cost should be achieved.

2. U-shaped Profiled Glass

U-shaped profiled glass is produced from cast glass with a thickness of 6 to 7 mm, width between 230 to 500 mm and length up to 7 m. The surface can be structured, as well as clear. Due to their statically favorable U-shape, cost-efficient single and multiple glazed façades with large spans without transom can be realized. The individual glasses are attached using an aluminum frame. The glasses are inserted individually into the frame. Designed as a multi-layer, coated system, U-values of up to 1.1 W / (m²K) can be achieved (assembly with low-emissivity coating). Figure 1 shows the model and schematic design of a double-shell profiled glass façade system.





Fig. 1: Model (left) and schematic representation (right) of a façade system consisting of double-shell U-shaped profiled glass

Profiled glass is mainly used for industrial and commercial applications but also for residential and public buildings such as schools, theaters and museums. Usually there, where a large amount of daylight is desired or required. However, the experience shows that the supply of daylight is often higher than the demand and that the requirements for visual comfort can be still fulfilled even by significantly reducing the transparency of the building envelope. Depending on the building typology and use, it is necessary to check what percentage of the façade is available for the active use of solar energy.

3. Solar-activated U-shaped Profiled Glass

The development is based on the double-shell profiled glass façade system outlined above. The solar thermal activation is achieved by inserting a metallic absorber into the air gap between the two profiled glasses. Suitable spacers are provided to place and center the absorber in the gap so that contact between the absorber and the profiled glass is prevented. In the selection of geometry and materials of the spacer in addition to the cost, in particular the requirements on temperature stability and aesthetics must be considered. The heat transfer between the solar absorber and the solar circuit takes place via heat pipes, which are thermally coupled to the solar circuit by means of a dry connection. Compared to direct flow collectors, collectors with heat pipes exhibit the following advantages, especially for façade applications and specific for the integration in profiled glass:

- Compatibility with the modular assembly of the profiled glass system
- Significantly smaller amount of heat transfer medium (approx. factor 100) and thus lower weight
- Simpler hydraulic circuit and thus easier integration into the façade system
- Low pressure drop and easy venting
- Possibility to set the maximum temperature of the system by properly dimensioning the heat pipe (type and amount of the heat transfer medium) to avoid overheating.

In addition to the advantages listed, one significant disadvantage has to be mentioned: Heat pipes represent an additional thermal resistance between the solar absorber and the solar circuit. The efficiency of collectors with heat pipes is lower than that of collectors with direct flow. For an efficient use of this advantageous technology, the thermal connection to the manifold is particularly important.

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Based on the experience at the ISFH with already completed or ongoing projects on the use of heat pipes in solar thermal applications, the theoretical potential of the zero-loss efficiency value was determined according to the thermal equivalent circuit diagram shown in Figure 2. Typical values of the individual heat transfer coefficients at the absorber U_{abs} , the heat pipe U_{hp} and the manifold U_{mf} are used for the further calculation. The manifold heat pipe coefficient typically ranges between 5 W / K for manifolds with plug-in sleeve and 10 W / K for hydro-formed manifolds with clamp connection. The heat pipe heat transfer coefficient with an organic working fluid is between 2 and 4 W / K (depending on the condenser temperature and the thermal output), whereby heat pipes with water as working fluid can reach heat transfer coefficients above 15 W / K (Jack et al., 2013). In this case, heat pipes with an organic heat transfer medium are used in the first step. This makes it possible both to limit the maximum temperature that occurs at the manifold (avoidance of stagnation damage) and to guarantee a frost-free operation of the system (Schiebler et al., 2018).



Fig. 2: Thermal equivalent circuit diagram of an absorber strip including the manifold. Color design of the individual heat transfer coefficients (manifold U_{mf} , heatpipe U_{hp} , absorber U_{abs}); heat loss coefficient U_{loss} ; internal heat transfer coefficient U_{Int} ; absorbed heat flow \dot{Q}_{abs} ; useful heat flow \dot{Q}_{gain} ; heat loss flow \dot{Q}_{loss} ; zero-loss efficiency η_0 as a function of the effective transmission-absorption product ($\tau \alpha$)_{eff} the internal heat transfer coefficient and the heat loss coefficient.

Assuming a specific absorber heat transfer coefficient U_{abs} of 30 W / K, a heat loss coefficient of 5 W / (m²K) typical for flat-plate collectors (in relation to the absorber area) and a transmission-absorption product of 0.83 (solar transmittance glass 0.86, solar absorptance 0.95), the zero-loss efficiency value depends on the heat pipe and manifold heat transfer coefficients. As shown in Figure 3, under the assumptions made, zero-loss efficiencies up to approx. 0.75 are possible. To achieve this value, a manifold with a specific heat transfer coefficient of at least 15 W / K and a highly performing heat pipe with a specific heat transfer coefficient greater than 10 W / K must be used. For the profiled glass collector, an optimization of the manifold and condenser geometry is carried out within the scope of this work in order to achieve higher specific heat transfer coefficients compared to the geometries customary on the market.



Fig. 3: Zero-loss efficiency η_0 as a function of the manifold and heat pipe heat transfer coefficients (U_{nf} and U_{hp}) with an absorber heat transfer coefficient (U_{abs}) of 30 W / K, heat loss coefficient (U_{loss}) of 5 W / (m²K) and an effective transmission-absorption product (($\tau \alpha$)_{eff}) of 0.827 (in relation to the absorber area per heat pipe of 0.132 m²)

First investigations focus on solar absorbers consisting of standard metal sheets provided with spectrally selective or non-selective coatings. By using colored coatings, the arrangement and the nature of the absorber sheets, a high architectural design freedom can be achieved (e.g. use of perforated sheets). This relates on the one hand to the aesthetic appearance and on the other hand to the supply of daylight to the building. Figure 4 shows schematically exemplary possibilities for controlling the daylight supply.



Fig. 4: Perforated absorber sheets to increase the daylight supply (left); Façade design options with colored absorbers and alternating arrangement of transparent, conventional and opaque, solar-active U-shaped profiled glass (right)

4. Experimental Evaluation of Solar-active U-shaped Profiled Glass Modules

Based on the theoretical consideration of the specific heat transfer coefficients, different large-format, solar-activated u-shaped profiled glass modules were manufactured and experimentally investigated. Figure 5 shows the schematic design and a large-format sample.



Fig. 5: Schematic representation of the façade profile with integrated, solar thermal absorber (left) and a test façade module (right; variant with non-selective black absorber)

Efficiency parameters as well as the maximum temperatures occurring in the module and on the glass surfaces under stagnation conditions were determined on a 2 m² profiled glass sample under artificial irradiation according to the ISO 9806 Standard (ISO, 2018). These temperatures play an important role in the development both with regard to the resistance of materials and components and to the question of thermal comfort in the interior (radiant heat of the glass interior surface). The façade module was examined in different configurations. In the individual versions, two different absorbers (selective and non-selective), two different front profiled glass (ferrous and low-iron variants) and two measures to reduce rear heat losses (low-emitting coating; additional 3 cm thick insulation on the rear of the absorber) were tested. A total of four different variants were examined, which are shown schematically in Figure 6 to illustrate the respective structure.

The different configurations led to zero-loss efficiencies η_0 related to the aperture area in the range from 0.51 to 0.59 as well as to heat loss coefficients a_1 in the range from 3.8 to 5.8 W / (m²K) and a_2 from 0.01 to 0.03 W / (m²K²). The results of the specific variants are shown in Table 1.



Fig. 6: Schematic sectional view of the investigated variants with technical data of the components

Variant	Description	ηo	$a_1[W/(m^2K)]$	$a_2 [W/(m^2 K^2)]$
1	front glass: $\tau=0.87$ absorber: $\alpha=0.95$; $\epsilon=0.86$ rear glass: low-e coating $\epsilon=0.15$	0.51	5.8	0.030
2	front glass: $\tau=0.87$ absorber: $\alpha=0.95$; $\epsilon=0.86$ rear insulation: 3 cm; $\lambda=0.035$ W/(mK)	0.54	5.6	0.017
3	front glass: $\tau=0.87$ absorber: $\alpha=0.95$; $\epsilon=0.04$ rear insulation: 3 cm; $\lambda=0.035$ W/(mK)	0.59	3.8	0.012
4	front glass: τ=0.82 absorber: α=0.95; ε=0.04 rear insulation: 3 cm; λ=0.035 W/(mK)	0.54	3.8	0.012

Tab. 1: Efficiency parameters of the investigated variants related to aperture area

The comparison of variant 1 to variant 2 shows that thermal insulation applied to the rear side of the absorber can reduce heat losses and thus also improve the zero-loss efficiency. The heat losses are further reduced in variant 3 by using a spectrally selective, low emissivity absorber coating, so that a zero-loss efficiency of 0.59 related to the aperture is achieved. The reported value is still significantly lower than those of a standard flat plate collector (0.75 – 0.80). This depends on the one hand, on the lower solar transmittance of the low-iron cast glass used (0.87), compared to typical values of low-iron flat glass (0.90) and, on the other hand, on the effective absorber area of the profiled glass collector. The absorbers only occupy around 80 % of the aperture, so that the remaining 20 % is not used for the active production of thermal energy but still available for daylight supply. This aspect must be considered for a holistic performance assessment of the façade system, as this type of solution is typically used in buildings with a high demand for daylight. The first system simulations on a reference building show that visual comfort is not adversely affected if up to 50% of the façade area is covered with solar-activated u-shaped profiled glass modules.

In order to evaluate the performance of the manifold / heat pipe configuration used and compare it to the state-of-the-art, the results should be referred to the absorber area. Under this assumption, for example, variant 3 has a zero-

loss efficiency of 0.75. Considering the theoretical parameter study shown in Figure 3, this result proves that the manifold and heat pipe solutions implemented for the manufactured modules ensure very good heat transfer from the absorber to the solar circuit fluid.

To estimate the maximum expected thermal load occurring on the individual components and on the glass surface temperatures during operation, the façade modules were exposed to artificial radiation over a period of 5 hours. To compare the configurations with each other, the standard stagnation temperature (irradiance of 1000 W / m^2 and 30 °C ambient temperature, no wind) of the individual surfaces was calculated based on the extrapolation method according to DIN 4757 (DIN, 1995). This resulted in maximum absorber temperatures for the non-selective variant 2 of 133 °C and for the variant 3 with selective absorber of 183 °C. These conditions lead to a room-side glass surface temperature of 45 °C for variant 2 and 52 °C for variant 3 respectively.

To analyze the performance of larger elements usually implemented in real buildings, a 4 m² (4 m x 1 m) module was manufactured with a non-selective absorber ($\alpha = 0.95$; $\varepsilon = 0.86$) provided with rear-side insulation as for variant 2 (Table 1), but exhibiting a ferrous front glass ($\tau = 0.82$). The measurement was carried out by means of an outdoor sun tracker. In our first measurements at normal incidence angle we reported a zero-loss efficiency η_0 of 0.44. The large difference of 10 percentage points compared to the variant 2 of the 2 m² module results both from the lower solar transmittance of the front glass ($\Delta \tau = 0.05$) and from a lower internal thermal coefficient due to the larger absorber surface and thus to the correspondent thermal power transferred per heat pipe. The size-dependent performance of the module has to be taken into consideration for the design and assessment of the specific façade solution.



Fig. 7: Large test façade module during the measurement on the sun tracker at ISFH (4 m x 1 m)

5. Evaluation of the Module in a Real Building

In order to evaluate the constructive aspects of the façade integration and the behavior of the new development under real installation conditions, a demonstration module according to variant 3 was installed in the façade of a production hall, featuring double-shell U-shape profiled glass. We measured the surface temperatures of the individual components of the module, focusing on the maximum temperatures occurring on the room-side glass surface, which are directly compared with the temperatures of a reference, non-activated module of the existing façade. Main goal of this investigation was the assessment of the impact of the solar activated module on the thermal comfort as a consequence of the higher solar absorption, both under summer and winter conditions. For this purpose, the solar module is operated during the entire exposure phase under stagnation conditions (unfilled solar circuit or collector). The temperature on the room-side glass surfaces and on the absorber is measured by using a Pt-100 chip sensor placed at 2/3 of the aperture height. In addition, the hemispherical irradiance on the façade (south-east orientation, azimuth angle = -54°) as well as the outdoor and indoor air temperatures are recorded. Figure 8 shows both the reference (a) and the demonstration solar module (b) integrated into the façade of the production hall.



Fig. 8: Façade-integrated, solar-activated profiled glass module (b) and reference profiled glass module (a), with sensors for recording the temperatures and hemispherical radiation (glass surface and absorber temperature placed at 2/3 of the aperture height)

Figure 9 shows the frequency distribution of the room-side glass surface temperature of the solar-activated and reference profiled glass modules over the measurement period from May 20th, 2020 to June 30th, 2021. During this period, the data were recorded with a measurement interval of one minute for a total time of 9382 hours. The respective monthly maximum and minimum values of the recorded temperatures as well as the hemispherical irradiance are given in Figure 10.



Fig. 9: Frequency distribution of the room-side glass surface temperature of the solar-activated and the reference profiled glass module (top: entire exposure period; middle: 20.05.2020 to 30.09.2020; bottom: 01.10.20 to 31.03.2021). The temperature class refers to an interval of ± 2.5 ° C around the class value





The frequency distribution over the measurement period as well as the monthly maximum values show that the investigated solar thermal module does not lead to an increased thermal load for the interior of the building in the summer months in comparison to the reference module. It should be noted that maximum absorber temperatures up to approx. 150 °C were recorded in the façade installation, which are 30 K lower than the measured stagnation temperature of the modules under test conditions. The temperature frequency distribution for the months October to March as well as the monthly minimum values show, on the other hand, that the module has higher temperatures compared to the reference module. This results in a lower effective U-value, which has a positive effect on the transmission heat losses of the building. For a more detailed assessment with respect both to comfort and performance, real operation conditions referred to specific applications (domestic hot water preparation, space or industrial heating) have to be taken into consideration. For this purpose, building simulations based on the experimentally determined efficiency parameters of modules with different design are planned.

6. Acknowledgments

The investigations presented in the work are part of the research project "Solar Profil", which is funded by the German State of Lower Saxony and by the German Federal Ministry of Economic Affairs and Energy based on a decision of the German Federal Parliament (reference number 16KN070723). The project is carried out in cooperation with the companies Flachglas Sachsen GmbH and Eilenburger Fenstertechnik GmbH. The authors are grateful for the financial support and responsible for the content of the paper.

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Design and Testing of Autonomous Curtain Walling Façade Unit

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Abstract

This paper presents an innovative concept of autonomous unitized curtain walling façade with integrated functions of heating, cooling, lighting, shading as well as renewable energy generation (photovoltaics) and storage (battery) within the façade system. The autonomous unitized façade unit has been designed, manufactured and tested in real environment. The façade unit achieves high level of autonomy in summer when solar shading is applied even though the efficiency of thermoelectric cooling resulted in significantly lower values than predicted.

Keywords: photovoltaics, thermoelectric cooling, Peltier cooling, curtain walling façade

1. Introduction

In most applications the prefabricated unitized curtain walling façades are passive elements which ensure thermal resistance between indoor and outdoor environment and solar shading of transparent parts. Efforts for increasing of renewable energy supply in buildings result in application of building integrated photovoltaic (PV) systems (Shukla et al., 2017). Advanced solutions of adaptive façades with various mechanical, electrical, thermal or chemical concepts have been investigated for last decade but the implementation in practice represents a challenging task (Loonen et al., 2017). The presented autonomous concept of curtain walling façade integrates infaçade thermoelectric air-conditioning unit together with renewable energy system consisting of PV panels and flat-plate battery within the façade structure. The target is to achieve a high degree of self-sufficiency in the energy balance for thermal conditioning of indoor space adjacent to façade (Zavrel, V. et al., 2019), especially in summer season for solar cooling. The demonstration unit for autonomous operation has been designed and manufactured in collaboration with industrial partner and its energy performance has been monitored for one year at test cell in central Europe climate to provide indoor comfort (space heating and cooling).

2. Design of Autonomous Curtain Walling Façade Unit

The developed prototype of façade module with size 3,06 x 2,75 m consists of three parts: part (1) with Peltier air-conditioning (heating/cooling) unit, part (2) with flat-plate battery unit and part (3) with triple glazed window and shading device (see Fig. 1). The construction of curtain-wall structure has been designed according to the standards of industrial partner WIEDEN s.r.o. with total *U*-value in opaque part 0,152 W/m²K. PV panels cover the whole available area of the module except the glazed part and air intake-exhaust openings. In total 8 polycrystalline PV panels are mounted at module considering efficiency 17,0 % with total peak power 920 W_p. Thickness of curtain walling unit assembly is 246 mm and the total thickness of the entire façade unit including ventilated cavity behind PV panels is 406 mm. To comply with the standard thickness of the curtain walling module structure was critical for the integration of energy components.

Part (1) of the façade module integrates the air-conditioning (AC) unit using thermoelectric Peltier elements. It was designed with 10+10 thermoelectric elements in two rows with considered operational cooling power 320 W each row (at operating point 12 V, 7 A). Only 10 elements were finally operated, rest of them were considered only as a back-up. The thermoelectric elements were thermally connected to fin heat exchangers at both so-called cold and hot sides of the elements. The remaining surface of the dividing plane between both sides is filled with immersed thermal insulation to eliminate the thermal bridging across the air channels. Fig. 2 (left) shows the

aluminium heat exchangers coupled to thermoelectric elements within the AC unit. Air circulation in channels at both hot and cold side is provided by small radial fans with variable speed control. While maximum airflow of both fans was considered at 800 m³/h, the speed levels of the exterior and interior fans were set differently for winter and summer regime. The winter regime was set at 3800 rpm (approx. 600 m³/h) for interior fan and 1900 rpm (approx. 300 m³/h) for exterior fan. The summer regime was set at 2800 rpm (aprox. 450 m³/h) for interior fan and 4200 rpm (approx. 650 m³/h) for exterior fan. AC unit can be operated in heating and cooling regime only by switching the polarity of the thermoelectric elements. In summer, the air from adjacent air-conditioned space enters the interior channel, where it is cooled down and delivered back to the conditioned space. The waste heat from the hot side of the thermoelectric elements is removed to the ambient environment via the exterior channel. The winter operation is reversed.



Fig. 1: Section view of three parts of autonomous curtain walling façade module covered by PV panels: (1) integrated AC unit with thermoelectric elements, (2) integrated flat-plate battery unit, (3) window with solar shading device



Fig. 2: Peltier AC unit with finned heat sinks (left), flat-plate battery layout (right)

Part (2) of the façade module reflects the standard layout of opaque curtain walling facade but it integrates a flatplate battery unit in cavity at interior surface of the module. This location ensures satisfactory operational conditions as well as good access for the maintenance from the interior. The flat-plate battery unit is composed from 2 sections, each contains 8 LiFePO4 cells (3,2 V; 60 Ah), see Fig. 2 (right). The whole battery unit is only 25 mm thick and its nominal energy capacity is 3,1 kWh. Individual battery cells are connected to battery management systems to control uniform charging/discharging and monitoring of battery cells status. The whole system PV – battery – AC unit is connected into the direct current (DC) circuit and operated at nominal voltage 24 V.

Last part (3) of the façade module represents a standard glazed curtain walling structure with controllable shading system according to the standards of the industrial partner. The triple glazing unit ($U_g = 0.5 \text{ W/m}^2$.K, g = 0.5) is

applied to introduce a natural daylight into the adjacent space. The external louvers with servomotor powered by DC current were located in the upper part.

3. Testing and long-term monitoring

The manufactured façade module has been installed to a test cell (see Fig. 3) for demonstration of the function and monitoring of operation parameters in September 2020. The test cell is divided to air-conditioned space (with floor area 3 x 3 m and height 2,6 m) and technical room with auxiliary cooling and heating circuits, thermal storage and detailed monitoring equipment to evaluate the energy flows within the testing cell and the tested façade system. Conventional indoor air temperature settings have been used for control (21 °C for heating, 27 °C for cooling, hysteresis 1 K) of the thermoelectric AC unit. Auxiliary space cooling and heating systems have been operated with shifted settings (18,5 °C for heating, 28,5 °C for cooling, hysteresis 1 K) to evaluate the thermoelectric AC unit capacity to cover the space heating and cooling load. Auxiliary space cooling has been provided by water/air fan-coil supplied with chilled water. Electric fan-coil provided the auxiliary space heating. Ambient air temperature and solar irradiance have been monitored as outdoor climate conditions, indoor temperatures were monitored in several places for control and to obtain an information about capability of façade module to keep the required conditions in the air-conditioned room.



Fig. 3: Installation of autonomous curtain walling façade unit at test cell (CVUT UCEEB)

Energy balance of the system (PV and battery electricity supply, façade load, back-up energy demand) has been monitored in detail to evaluate on-site energy fraction (OEF) and on-site energy matching (OEM) indicators. The OEF indicator is defined as the ratio of energy production from the PV system (including the battery) which covers the total energy consumption of the façade module and expresses the solar fraction or self-sufficiency of the façade module. The OEM indicator represents the ratio of the energy from the PV system (including the battery) used for local consumption to the total production of PV energy and expresses self-consumption of façade module. Efficiency indicators for thermoelectric heating and cooling (AC unit) has been also evaluated, namely coefficient of performance (COP) and energy efficiency ratio (EER) as the ratio of heating or cooling output to electric power input. Beside the PV panels as a part of the façade module, electricity from grid has been used as for back-up in case that battery state of charge will drop under 20 %. Following power quantities were monitored:

- electric power supplied from PV panels;
- electric power supplied from flat-plate battery;
- battery state of charge;
- total electric load of facade module;
- excess PV power exported out of system (heating rod in water storage);
- electric load of thermoelectric elements (negative cooling, positive heating);
- electric load of fans;
- back-up electricity from grid;
- back-up heating power;
- back-up cooling power (based on water flowrate and temperatures);
- cooling and heating power of AC unit (based on air flowrate and temperatures in air ducts).



Fig. 4: Course of electric power (production, load) for selected days in winter, spring and summer





The measurements have been taken with periodicity of half minute and logged to a cloud repository. Energy performance was evaluated from the measurements for period from October 2020 till September 2021. The PV production could not be measured in first month of the evaluation period due to fault of the battery system. During the long-term monitoring campaign, various manual interventions to the façade module operation were made. In November, the winter regime for fans was set after trial period, when various settings were tested. In January and February, the internet connection was lost for few weeks, that led to higher percentage of missing data. These part of monitoring data was not evaluated. In the beginning of May, the summer regime for fans was set. In the end of

June, the external shading has been applied and the auxiliary cooling system was switched off.

Data for a detailed evaluation have been selected from five working days, when the required temperature conditions were to be met, in three different periods (winter, spring, summer). Fig. 4 shows the course of power supplied and consumed by the curtain walling façade unit. Supplied electric power (production, with a positive sign) is differentiated according to the source: from the grid, supplied from the battery and at the same time the power of the PV system supplied to the battery, or excess power wasted by the electric heater in the heat storage tank. Measured surpluses in the storage tank represent the export of electric power back to the grid. Consumed electric power (load, with a negative sign) is differentiated according to the appliances: consumption of thermoelectric elements (TEM) and fans divided for heating or cooling purposes, and consumption of the power of other measurement and control components. Consumption of auxiliary heating and cooling is not included in the graphs.

In Fig. 5, the indicators OEF and OEM are expressed on daily basis for given periods. The autonomous curtain walling façade unit did not cover a relatively high cooling load with open blinds in the summer months with its cooling capacity and auxiliary cooling was necessary, however, in the case when blinds were used and in the transition period (spring) the results were significantly better. In terms of covering the electricity demand, the results were very good in the transition period and number of days in the summer showed a high degree of autonomy. In winter, due to the low production of the PV system, there is a high utilization of PV production (OEM), but naturally with a very low solar coverage (OEF).

A more detailed analysis of the results showed that the PV facade exposed to sunlight reaches relatively high temperatures around 50 to 60 °C, which causes a reduction in the useful cooling capacity of the AC unit adjacent to outer surface of the facade. Despite the efforts to avoid significant thermal bridges, too large dimensions of the AC unit do not allow to achieve a designed cooling capacity of around 320 W in real operation.

The summarized monthly results are presented in Table 1 which contains timestamp, percentage of missing data, monthly total electrical consumption and PV production as well as heating/cooling delivery and demand coverage. Table 2 shows the monthly values of indicators OEF and OEM and also monthly values of thermoelectric AC unit energy efficiency using COP for heating efficiency and EER for cooling efficiency.

Year	Month	Missing data	Total el.PVHeating deliveryCooling deliveryloadproductiand demandand demoncoveragecoverage		Heating delivery and demand coverage		delivery emand rage	
[-]	[-]	[%]	[kWhel]	[kWhel]	[kWht]	[-]	[kWht]	[-]
2020	10	3	267,9	nan	15,8	0,59	0,4	0,17
2020	11	0	321,6	24,2	24,4	0,71	0,0	nan
2020	12	0	361,4	15,2	144,5	0,90	0,0	nan
2021	1	17	351,6	21,3	192,1	0,95	0,0	nan
2021	2	21	272,8	33,3	135,4	0,74	0,0	nan
2021	3	2	278,0	43,2	135,8	0,96	0,8	1,00
2021	4	0	192,9	44,9	73,3	0,95	0,4	1,00
2021	5	0	101,5	48,5	13,1	0,75	0,0	nan
2021	6	0	166,1	51,4	0,3	1,00	4,1	0,15
2021	7	0	47,9	41,7	0,2	0,55	0,1	1,00
2021	8	0	59,0	33,7	1,5	0,70	0,2	1,00
2021	9	0	44,2	25,4	2,8	0,80	0,0	nan

Tab. 1: Energy balance of autonomous facade module

Year	Month	Missing data	OEF	OEF OEM COP EE		СОР		ER
[-]	[-]	[%]	[-]	[-]	monthly [-]	max. [-]	monthly [-]	max. [-]
2020	10	3	nan	nan	0,08	0,99	0,34	0,39
2020	11	0	0,08	0,98	0,10	0,46	0,05	0,17
2020	12	0	0,04	1,00	0,46	2,16	nan	nan
2021	1	17	0,06	1,00	0,62	3,32	nan	nan
2021	2	21	0,12	1,00	0,57	1,13	nan	nan
2021	3	2	0,16	0,99	0,58	1,75	0,17	0,22
2021	4	0	0,24	0,99	0,46	1,91	0,20	0,24
2021	5	0	0,48	0,97	0,18	0,64	0,00	0,17
2021	6	0	0,31	0,99	0,16	0,38	0,05	0,33
2021	7	0	0,86	0,90	nan	nan	0,01	0,11
2021	8	0	0,56	0,91	0,08	0,26	0,01	0,11
2021	9	0	0,57	0,92	0,09	0,25	nan	nan

Tab. 2: Energy efficiency indicators

4. Conclusion

The energy performance of the unitized curtain walling façade unit designed with integrated energy components to achieve high autonomy was experimentally evaluated in the long-term monitoring campaign to evaluate the operation under real-life conditions. In terms of energy autonomy, the main focus was set on power self-sufficiency in summer season and on potential for so-called solar cooling. The maximum level of self-sufficiency was in July, when 86 % of the power load was covered by the on-site generation. The key factor here was an application of exterior shading, which led to significant reduction of cooling demand and related total electric consumption. The power self-sufficiency in winter season was not expected based on the preliminary calculations and the experiment proved the assumptions. The self-sufficiency in the winter season was only around 10 %.

Use of only 10 thermoelectric elements (nominal cooling power 320 W) was not satisfactory to cover peak cooling loads especially in case without shading. For example, in June only 15 % of cooling load was covered by Peltier AC unit system. Otherwise, in off-season or with external shading, the unit was able to cover the needs of the testing cell and reduce the overheating hours. Although the capacity was reduced, the heating demand coverage was relatively high during winter season (October till March) at approximately 80 % in average, but with electricity taken from the grid.

The Peltier AC unit performed below our expectations in term of energy efficiency. The COP was found between 0,8 to 0,6 (expectation from preliminary laboratory experiments was 1,2 to 2,0). The EER was determined around 0,1 to 0,2 (expectation 0,6 to 1,0). The efficiency is worsened with the reduced operation of the AC unit due to thermal bridges between hot and cold air channels resulting with higher value of temperature of cold air incoming to the room as well as with the thermoelectric elements efficiency reduced due to high temperature of exterior façade surface. The fan speed setting was found also inappropriate therefore the ongoing work will be focused mainly on the optimizing of fan control settings, elimination of thermal bridges and proper control of shading device.

5. Acknowledgments

This work has been supported by the Technology Agency of Czech Republic within the project TH03020341 Autonomous curtain wall panel.

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M-04. Zero-Energy or Plus-Energy Buildings/ Neighborhoods

IMPLEMENTATION OF SOLAR STRATEGIES WITHIN DIFFERENT URBAN LAYOUTS

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ABSTRACT

This work presents the process of solar strategies implementation on the neighborhood scale. A novel methodology is developed that initially uses a data collection matrix to record various features of neighborhood archetypes required for energy modeling. This work then selects three distinct neighborhoods in Canada based upon different attributes related to building type. Various tools and resources such as GIS, censes data, and building codes are used to gather the matrix data for these three neighborhoods. Subsequently, energy modeling of these neighborhoods is carried out using EnergyPlus to analyze their energy performance. Upon the identification of suitable solar surfaces, various solar strategies will be proposed and simulated by using PVSyst.

Keywords: Neighborhood archetypes; data collection matrix; energy modeling; energy analysis; solar strategies.

1. Introduction

More than half of the world's population lives in urban areas since 2007, resulting in the development and growth of different sectors of the economy, significantly increasing the urban energy demand, as well as an urge to a change in the fuel mix (Madlener & Sunak, 2011). With the recent advances in technology, new methods to generate and conserve energy have surfaced, and others became more viable to be installed. One of the biggest challenges public authorities are facing is to decrease the use of fossil fuel and rely more on a renewable energy-based source. Renewable sources of energy, especially solar, are turning into a key component in designing new energy efficient buildings that aim at achieving net zero energy status. Energy efficiency is the condition of using less energy while maintaining the same level of performance (Beckett, 2018). While this objective is feasible on a building scale, it is more challenging on a neighborhood scale. The urban design has a major influence in the energy demand of buildings and transport (Hachem, 2016).

As a step towards developing strategies of solar net zero energy neighborhoods, the International Energy Agency (IEA) Task 63: Solar Neighborhood Planning developed a matrix to catalog different patterns of neighborhoods, classifying them by neighborhood types and use, street layouts, building designs and several other neighborhood parameters. This matrix is employed to standardize energy simulations on large scale. Having this in mind, this paper aims to investigate selected solar strategies that have an effective impact on the energy consumption of different types of neighborhoods.

2. Methodology

The methodology is divided into four phases. Initially, a broad analysis of the urban patterns of the selected area to study is needed to identify repetitive layouts that can be used as a representative of a typical neighbourhood. After validating that the selected neighbourhood to study has a common urban layout, the second phase of the methodology comes in-place. It includes the development of 3D models to extract data, based on georeferenced mapping. Moreover, different data to input in the energy model should be collected via regional census, building codes and other relevant sources. The matrix is developed to compile relevant neighborhood archetype data for energy modelling needs to be filled. This data will be then used to establish the energy models for three neighborhoods. Finally, some solar strategies to these three neighborhoods will be proposed. Since this methodology is applicable for existing neighbourhoods in this study, the matrix acts as an innovative tool that eases the analysis process of both existing and new neighbourhoods.

© 2021. The Authors. Published by International Solar Energy Society Selection and/or peer review under responsibility of Scientific Committee doi:10.18086/swc.2021.44.01 Available at http://proceedings.ises.org

2.1. Urban Patterns

The very first step when selecting a neighbourhood to evaluate its energy performance is to find if the urban pattern is a representative of the usual layout present in the region where it is located. This is an essential step in order to validate the developed model to a baseline that is compatible to a typical neighbourhood, otherwise the energy simulation might not have an accurate reference.

For the presented case study, based on different street layouts displayed in the IEA Matrix, the three selected neighbourhoods' layout were compatible to at least five other neighbourhoods across Canada, having the same characteristics, such as: conventional and tilted grid, variants of attached and detached houses, similar type of construction and rooftop, and other details. The analysis was made using the mapping software Google Earth Pro, making the visual evaluation a key tool for this study.

2.2. Selection of neighbourhoods

Using the matrix described below, three neighborhoods are selected and analyzed for the comparison, in different regions of Canada. A crucial part of selecting regions is the availability of data. The study counts on data of community profiles and energy standards collected from reliable sources, such as Statistics Canada (2016) and Natural Resources Canada (2019), to structure and support the simulations of neighborhoods. The first neighborhood, East York, located in Toronto, Ontario (43.689275°, -79.337520°), climate zone 5, is a conventional neighborhood with low-rise buildings composed with only detached houses. The second neighborhood, Saddle Ridge, located in Calgary, Alberta (51.128769°, -113.930133°), climate zone 7A, is a mixed of detached and attached houses, presenting also low-rise buildings and a mix of conventional and curvilinear grid layout. Finally, the third example, Mount Pleasant, located in Vancouver, British Columbia (49.258019°, -123.105317°), climate zone 5, is a mixed neighborhood with high-rise buildings, multi-family, as well as detached single-family dwellings. Just a small portion of the area is selected to be analyzed within the neighborhood and serve as a sample of the presented urban design to ease the simulation process.

2.3. Neighbourhood data collection matrix

The proposed study presents a Matrix developed by IEA Task 63 - SubTask A (International Energy Agency, 2021) to assist in the data input when simulating energy efficiency of larger urban areas. The matrix is a spreadsheet that allows input data of neighborhoods' characteristics, divided into five general categories: (A) Type of Neighborhood, (B) Neighborhood Building Structure and Passive Design, (C) Solar Energy Generation, (D) Energy Systems, (E) Miscellaneous Information, and (F) Simulation Outputs. In every category, several items are listed to collect information of different types of neighborhood archetypes, such as: street layout, green areas, density indicators, building type, block design, usage type, roof design, façade characteristics, geometry, shading devices, and others. These archetypes are then simulated, and their energy performance is compared.

Filling data into the matrix is a process that should be thoroughly considered. Different tools can be used to fill the matrix, including mapping software such as Google Earth, Open Street Map, ArcGIS, and others that will combine with 3D modeling software, like SketchUp, AutoCAD, Rhino, and others to develop a model of each neighbourhood. With a 3D model in place, essential data to generate an energy model can be extracted from it, like floor and rooftop areas, shading analysis, window to wall ratio, and much more. A possible variation of around 5% from the is expected when generating geometries out of real buildings.

Some other data that are not extractable from the model (mentioned above) needs to be addressed, like demographics for instance. Reliable data sources, such as Census and Regional Building Codes are also alternatives that have being exploited. Further, these data can be used for energy simulation and accordingly suitable solar strategies can be implemented.

The flowchart shown in Figure 1 illustrates the overall process taken by following this methodology to analyze the energy performance of the case study neighbourhoods.



Figure 1 - Methodology Flowchart

2.4. Energy modeling

The third phase of this methodology consists of inputting all the collected data into an energy modelling software to create a comprehensive energy model of the neighbourhood. For this specific study, EnergyPlus is chosen, an energy analysis and thermal load simulation tool. In combination with EnergyPlus, SketchUp and the plugin Euclid also is used to due to the ease of modelling a 3D structure and the integration with other platforms. This plugin employs SketchUp's modelling platform to convert energy data input from the 3D model into an EnergyPlus-compatible energy model. Satellite pictures are utilized to compute measurements for the 3D modelling of the neighbourhood structures. Furthermore, Google Street View and 3D models from Google Earth are applied to model the rooftops of the structures as accurately as feasible.

The following assumptions are taken into account in the modelling of the neighbourhoods studied in this study:

- a) The building shapes are based on the shape of the roofs.
- b) Exterior walls are considered to be 1 metre offset from the edge of the roofs, resulting in an overhang.
- c) Each floor is supposed to be 2.5 metres tall. Inside walls or any internal divisions of buildings were not considered.
- d) Fenestrations were created based on street views if available, and if not, on the patterns of adjacent buildings.
- e) In single-family structures, each home is a zone, whereas multi-family buildings include a zone for each unit and common area.
- f) Electric furnace is the heating system assumed for the energy simulations of all buildings due to its commonly use in north American buildings.
- g) The only enhancement studied and applied for the retrofit buildings is the building envelope.

Following the modelling of the specified neighbourhoods, an IDF file is created to be further processed and analyzed with Energy Plus.

When running a simulation in EnergyPlus, a lot of parameters that have a significant impact, such as HVAC systems, construction materials, lighting and appliances average use, and others, must be properly considered. Therefore, all the assumptions are based on data from the census, government agencies, on standard buildings and systems, and the 2017 ASHRAE Handbook – Fundamentals (ASHRAE, 2017). Energy simulations considers the energy demand of thermal zones by different end-uses over a full year.

The simulations include five energy end-uses, which are also considered in the NRCan Comprehensive Energy Use Database (Natural Resources Canada, 2019). Those are: Space Heating, Water Heating, Space Cooling, Appliances, and Lighting. Aiming to reach net-zero energy status, the building envelope is designed in two different types of material: conventional and high performance. This allows a comparison of energy performance while assessing the average reduction in the energy demand, especially on space heating.

For the standard construction, commonly employed materials are considered, like insulated wood frame walls, plywood floors, asphalt shingle roof coated with OSB boards, double pane glazing, and others. When simulating a high-performance version of the neighbourhoods, materials are generally selected to reduce the

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energy demand and increase the efficiency of the buildings, like highly insulated walls, roofs, and windows. The table below shows the various material components applied to the buildings in the energy model simulation.

Table 1 - Glazing Materials

GLAZING MATERIALS									
Name Thickness Solar Transmittance Visible Transmittance Conductiv									
6 MM Glass	6	0.775	0.881	0.9					
Bleached Film	12 0.014		0.947						
Glass 12MM	12	0.814	0.847	0.9					
Glass 12mm	12	0.653	0.841	0.9					

		Name	Thickness [mm]	Conductivity [W/m-K]	Density [kg/m³]	Specific Heat [J/kg-K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance	Thermal Resistance [m²- K/W]
	=	Synthetic Stucco	3.048	0.865	400	8.78	-	-	-	-
	3D: Wa	Sheathing Consol Layer	12.7	0.094	685	1172.33	-	-	-	-
	DAI	7/16 inch OSB	11	0.11	5.44	1.21	-	-	-	-
	AN	Wall Consol Layer	139.7	0.057	120.8	1036.25	-	-	-	-
	SI	1/2 inch Drywall	1270	0.16	8	1.08	-	-	-	-
		1 inch Stucco	25	0.69	1858	837	0.9	0.92	0.92	-
	Nall	8 inch HW Concrete block	203.2	1.311	2240	836.8	0.9	0.7	0.7	-
	HP: V	HP Wall Insulation	329	0.04	265	836.8	0.9	0.7	0.7	-
		1/2 inch Gypsum	12.7	0.16	784.9	830	0.9	0.92	0.92	-
ERIALS	STANDARD: Roof	Asphalt Shingle	6330	0.08	1.12	1.25	-	0.75	-	-
MAT		1/2 inch OSB board	1270	0.11	5.44	1.21	0.9	0.7	0.7	-
	oof	Roof Membrane	9.5	0.16	1121.29	1460	0.9	0.7	0.7	-
	a a	HP Roof Insulation	687.99	0.04	265	836.8	0.9	0.7	0.7	-
	ЧН	Metal Decking	1.5	45	7680	418.4	0.9	0.7	0.3	-
	RD:	Floor Consol Layer	234.95	0.05	55.07	916.93	-	-	-	-
	NDA Slab	3/4 inch Plywood	19.05	0.11	544.68	674.54	0.9	0.7	0.7	-
	f1S	Carpet	2540	6.01	32.03	8.36	0.9	0.7	0.7	-
	Slab	Heavyweight Concrete	101.6	1.31	2240	836.8	0.9	0.7	0.7	-
	<u>é</u>	HP Slab Insulation	44.39	0.049	265	836.8	0.9	0.7	0.7	-
	-	CP02 Carpet	-	-		-	0.9	0.7	0.7	0.2165

Table 2 - Construction Materials

The simulation of the neighbourhoods is followed by a comparison of the NRCan baseline (Natural Resources Canada, 2016) and validated based on the energy consumption per area (kWh/m²/year).

2.5. Solar analysis and strategies

Energy simulations play a crucial role in the on-site distributed generation of renewable sources to assess GHG emission reduction and to compare system yields across different urban layouts. The parameters used in each simulation may vary according to the characteristics of the environment that the system is installed, but the same system configuration must be used in all the simulation for comparative purposed, if possible.

The analysis of the three neighbourhood examples allow to assess several solar strategies implementation on an urban scale and their impact on energy performance. The paper explores the integration of these strategies into different urban and buildings environments, such as car shelters, building integrated Photovoltaics, standard roof PV systems, as well as the use of different technologies, like bifacial solar panels, and others. Simulations are conducted employing PVSyst, a standard in the solar industry, for solar energy generation simulation.

Before selecting the solar strategies that are most appropriate to each case, it is important to understand the characteristics and surroundings of where the system will be implemented. A shading analysis was developed to identify possible system's hiccups due to mutual or external shading, like trees, other buildings, and rooftops.

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The figure 2 illustrates a shading analysis showing the amount of time that each surface receives during certain periods of the day, and season. The shading analysis was done using a plugin for the SketchUp, called Shadow Analysis.



Figure 2 - Shading analysis of Saddle Ridge during Fall.

Solar strategies are divided into two different categories: active and passive. Passive systems are designs, building elements and everything around the building that optimizes the use of light and heat from the sun. On the other hand, active systems are devices that directly convert sunlight into usable forms of energy, like water heat and electricity.

A group of strategies are selected based on the characteristics of each neighbourhood. Several active and passive strategies are charted to clarify some of the usage of each, as well as a description of its concept. All the strategies listed were implemented in this study, but others can be considered when analysing the other case studies. BIPV were considered just as an active system in this study, but it's implementation also brings passive benefits to the building that were not considered due to the different software used to perform each simulation.

The following charts demonstrates active and passive solar strategies in the neighbourhood development.

Strategy	Technology	Description/Specifi cation	Rationale	Application
Rooftop PV	Solar Shingles, Polycrystalline, Monocrystalline and Thin Film solar modules	Installation of solar panels to seize enough solar energy for an adequate system performance and generation.	It is the most common active solar strategy. Great cost for the performance.	Tilted rooftops with good solar orientation and free of shading.
Flat rooftops PV	Bifacial, Thin Film and Monocrystalline solar modules	Installation of solar panels to seize enough solar energy for an adequate system performance and generation.	Due to the limited area of flat rooftops, high efficiency measurements should be applied to meet	Flat rooftops with limited area for PV installation. Use of bifacial panels or East- West mount

			the energy demands of multi-family buildings.	systems for higher energy output.
Carport	Bifacial solar modules	Installation of solar panels to seize enough solar energy for an adequate system performance and generation.	If case the use of rooftops is not enough to supply the energy needed, a car shelter mounted with PV panels will help in the energy generation.	Car shelters mounted with bifacial solar panels that will be installed in parking spaces as an alternative use of solar energy.
Solar Trees	Bifacial, Thin Film and Monocrystalline solar modules	Steel structures that resemble a tree but has solar panels at the end of each branch.	Aesthetic solution for open green areas that may still have an impact on the energy generation.	Applied in green open spaces, like public parks and walkways. Good alternative for places where visuals should not be disrupted.
Building Integrated Photovoltaic	Bifacial, Thin Film and Monocrystalline solar modules	Installation of solar panels on buildings components, integrated with the building.	Used to take advantage of building sections and turn it into an area of solar generation	Applied on building façades and other building components.

Table 4 - Passive Systems

Strategy	Technology	Description/Spe cification	Rationale	Application
Use of vegetation	-	Placing vegetation in appropriate areas that will help to shade buildings when needed.	Vegetation helps to reduce the cooling load of buildings. In the larger picture, it helps also to reduce the heat island effect, lowering the temperature within urban sprawls.	Natural shading element that is applied where direct sunlight might not be desired.
Use of high reflective building envelope	White paint or any material with high reflectance index	Using high reflective materials, especially on rooftops will help to lower the temperature by not retaining the heat from the sun.	By not absorbing solar heat, the building will lower its cooling loads and help to prevent global warming.	Use of high reflective materials on the building envelope or green roofs.
Use of overhangs	-	Overhangs are designed to block unwanted sunlight by covering windows.	If well sized, overhangs can block the sun on summer, when it is not desired, and let the	Apply on windows and any other openings that needs sunlight control.

			sunlight in on winters.	
Use of high- performance materials	Low-e triple pane windows, high insulated envelope, and others	Materials with high insulation that increase the air tightness of the building.	The use of high- performance materials will help to retain heat and cooling inside the building, reducing heating and cooling loads.	Materials used in the building envelope.

3. Results Analysis and Discussion

The yearly energy consumption is determined for each dwelling, including multi family buildings, and then summed to obtain the neighbourhood total energy. The simulations only consider buildings energy consumption, disregarding the energy usage of public infrastructures, such as public transportation, exterior lighting, and other services. These results are combinedwith the energy reduction of the application of high performance construction materials, and the energy generation potention using PV systems. The following figure illustrates the difference in generation by using different technologies, within different Canadian cities.

Table 5 - PV Systems Yield per city and technology

	PV System Yield by Technology in Different cities [kWh/kWp/year]				
Cities Rooftop Monocrystall		Bifacial - asphalt (albedo 0.1)	Bifacial - concrete (albedo 0.3)	Bifacial - white painted asphalt (albedo 0.9)	
Calgary	1140	1139	1181	1303	
Vancouver	995	999	1037	1150	
Toronto	1067	1082	1123	1247	
Winnipeg	1216	1206	1248	1371	
Montreal	1095	1109	1150	1273	

3.1. Energy Performance Results

3.1.1 Saddle Ridge, Calgary

The first simulated neighbourhood is Saddle Ridge, located in Calgary. It is composed of 54 dwellings, of which 48% are classified as detached houses and 52% are classified as attached houses. The total floor area is 8895 m², the average residential population is 4.1 people per dwelling and the heating system considered was furnace (Statistics Canada, 2016).

The simulated average space heating consumption for the conventional construction 134 kWh/m²/year, achieving a performance 9% better than the baseline, which is 148 kWh/m²/year. The average yearly overall energy consumption, considering space heating, cooling, water heating, appliances and lighting is 35,446 kWh per dwelling, and 215 kWh per m². The total yearly energy consumption of the neighbourhood is 1,914,068 kWh.

After the application of high performance materials in all buildings, the total yearly energy consumption reduced by 58%, mainly through the reduction of heating loads, achieving a demand of 1,093,992 kWh. The overall energy consumption per dwelling is 15,187 kWh, and 92 kWh per m².

The selected solar strategies employed in this case study is rooftop PV systems employingmonocrystalline 375W modules, utilizing the Canadian Solar module HiKu CS3L-375MS as a reference, and solar carports located in the attached and detached houses parking space, using bifacial modules, based on the Canadian Solar module BiKu CS3U-375PB-AG, with the same 375W of power. The albedo considered in the solar generation simulations for bifacial systems is 0.3. The overall power installed is 634.13 kWp, of which 377.63 kWp is monocrystalline modules applied on rooftops and 256.5 kWp is solar carports using bifacial solar panels. The

combined generation of all systems is 680,847 kWh/year, representing 35% of the initial energy demand of the neighbourhood.

SADDLE RIDGE	INITIAL Energy demand	Energy demand after retrofitting savings	Solar Energy Generation	RESULTS
kWh/year	1914068	1093992	680847	413145
% energy reduction	-	58%	35%	93%

Table 6 - Saddle Ridge Energy Performance

The total reduction in energy consumption after implementing solar strategies combined with retroffiting is around 93%, reducing the energy demand to 413,145 kWh per year. The addition of solar carports to the design helped to nearly achieve net-zero energy. However, these type of structures are usually much more expensive and might compromise the aesthetic looks of the residences, thus having a hard implementation proccess. The figure 3 shows the solar systems distribution and how it was employed according to the solar analysis study.



Figure 3 - Saddle Ridge Solar Systems Distribution

3.1.2 Mount Pleasant, Vancouver

The second neighbourhood analyzed is Mount Pleasant, located in Vancouver. It is composed by 133 dwellings, of which 23% are detached houses and the other 77% are apartments in low-rise buildings. The floor area has a total of 16615 m², combining the houses and apartment area. The predominant heating system is also furnace and the population per dwelling is 2.6.

The average space heating consumption per area (kWh/m²/year) is 79.5 for the detached houses, and achieving a performance 13.32% better than the baseline, which is 91.71. As for the apartments, the space heating consumption is 27.7 kWh/m²/year, a performance almost 39% better than the average apartment in the province of British Columbia. It is important to point out that the average size of the apartments in this neighbourhood is considered a little bit over 22% smaller than the average apartment in the baseline, impacting in the energy performance.

The average yearly overall energy consumption, considering space heating, cooling, water heating, appliances and lighting is 16,910 kWh per dwelling, and 135 kWh per m². The total yearly energy consumption is 2,249,052 kWh.

After applying high energy performance materials in all buildings, the total yearly energy consumption reduced by 33%, achieving a demand of 1,508,688 kWh. The overall energy consumption per dwelling is 16,910 kWh, and 91 kWh per m².

MOUNT PLEASANT	INITIAL Energy demand	Energy demand after retrofitting savings	Solar Energy Generation	RESULTS
kWh/year	2249052	1508688	791979	716709
% energy reduction	-	33%	35%	68%

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The solar strategies applied for this neighbourhood are the same as the previous case study for detached houses: rooftop PV systems using the same 375W monocrystalline modules. Those systems account for 359.25 kWp. Since the multi-family buildings has a limited rooftop area, an east-west mount strategy is designed to elevate the occupancy rate of the solar panels. This strategy allows to employ 378 kWp on two buildings. Two other smaller multi-family buildings employ bifacial modules arrays, totalling 55.88 kWp. Building Integrated Photovoltaic (BIPV), are employed as overhangs for the south facing windows. This strategy adds 65.25 kWp to the solar design. Lastly, solar trees are employed in public landscapes where there are minimal shading. Each solar tree has 8 solar panels, and by distribuiting 21 of these structures, it addsmore 63 kWp to the project. The total solar power installed on this neighbourhood is 870.38 kWp and the total generation is 791,979 kWh/year, covering almost 35% of the total energy demand of the buildings.

The total reduction in energy consumption after implementing solar strategies combined with retroffiting is around 68%, reducing the energy demand to 716,709 kWh per year. This design presents multiple solar strategies allowing the implementation of maximum amount of solar panels. However, due to a combination of lower solar radiation in Vancouver and non-ideal condiitons of some solar systemsleading to reduced performance, the neighbourhood is still 32% away from achieving net-zero status. Figure 4 illustrates the systems distribution and its solar analysis study.



Figure 4 - Mount Pleasant Solar Systems Distribution

3.1.3 East York, Toronto

The last neighbourhood analyzed is East York, situated in Toronto. The selected area presents 44 households, being all of them detached houses. Total floor area accounts for 5059 m^2 and the residential population per dwelling is 2.2.

The average space heating demand per area is 124.5 kWh/m²/year, having a better performance than the Ontario's baseline of just over 12%. The average overall energy consumption considering all the end-uses is 23,742 kWh per household, and 197 kWh per m². The total yearly energy demand is 997,176 kWh.

After the application of high performance materials in all buildings, the total yearly energy consumption reduced by 55%, achieving a demand of 445,896 kWh. The overall energy consumption per dwelling is 10,134 kWh, and 84 kWh per m².

EAST YORK	INITIAL Energy demand	Energy demand after retrofitting savings	Solar Energy Generation	RESULTS
kWh/year	997176	445896	505056	-59160
% energy reduction	-	55%	50%	105%

Since this neighbourhood is composed basically of detached single family houses, the main strategy implemented was the same as all the previous neighbourhoods for single family dwellings, which is filling the rooftops with the same monocrystalline panels and adding a solar carport on the parking space in front of each house. The rooftop PVs total an amount of 181.13 kWp, while the carports are responsible for 270 kWp. The multi-family building includes a 9.38 kWp system composed of bifacial modules installed on the flat rooftop, in addition to a BIPV of 6 modules, 2.25 kWp, that serve as overhangs for the south façade of the building. The total generation of the systems is 505,056 kWh/year, saving around 50% of the initial energy demand predicted.

The total reduction in energy consumption after implementing solar strategies combined with retroffiting is around 105%, generating 59,160 kWh/year more than what is consumed, reaching net-zero status. Following similar strategies to Saddle Ridge, East York benefits from a lower energy demand due to small-size houses and the implementation of solar carports as well. Figure 5 illustrates the systems distribution and its solar analysis study.



Figure 5 - East York Solar Systems Distribution

4. CONCLUDING REMARKS

The current study presents a new methodology to develop an energy performance analysis in a larger scale environment, considering the primary energy end-use of Canadian households, taking into account the implementation of retrofitting strategies combined with on-site solar generation.

The parameters included in this study are energy performance of a group of buildings, urban design, density, climate, and building type and use. The resulted energy performance is a balance between the initial energy demand, reducing the savings from the proposed retroffiting envelope and the employing of different solar energy systems. The achieve results points to East York achieving net-zero energy status, while Saddle Ridgeachieves near net zero energy status. Mount Pleasant is the neighbourhood that implements the most diverse solar strategies but still was far behind when trying to achieve net-zero status. The most effective strategy is the combination of solar carports utilizing bifacial modules, which is not implemented in the last mentioned neighbourhood, Mount Pleasant, because most of the housing garages are sheltered and located in the back alley, which was already used to install rooftop PV systems.

Although this methodology is applied to Canadian neighbourhoods, it can be replcated to different environments, serving as a guideline for possible future energy performance assessments on a larger residential and commercial areas. Some other locations might present different aspects that should be also considered, for

instance a different street layout, archetypes, different ways of consuming energy or even other sources of energy renewable application that might have a better performance and implementation in parts of the world.

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M-05. Zero- or Low-Carbon Emission Buildings/Neighborhoods etc

REDUCING AIR CONDITIONING ELECTRICAL DEMAND IN HOT ARID CLIMATES USING PV: A CASE STUDY IN JEDDAH, SAUDI ARABIA

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Abstract

Kingdom of Saudi Arabia (KSA) is one of the rich sunbelt countries in the world with very large potential for deploying solar photovoltaic (PV) technologies to support transitioning its dependence on fossil fuel dominated electricity sector. The hot arid climate of the country combined with its growing per capita income and cheaper electricity tariff makes KSA having the third largest electrical cooling load in the world. This research investigates how appropriately sized residential rooftop PV system can reduce such a load in KSA's residential sector addressing sustainability and emission reductions. Modelling was carried out to determine the efficacy of an optimally sized grid connected PV system to support different scenarios of the air conditioning loads of a monitored villa in Jeddah where the electrical demand was measured over a period of one year. Techno-economic suitability of the proposed system was analysed within the remit of Electricity Cogeneration and Regulatory Authority's (ECRA) current policy and regulatory framework for small scale solar PV systems. The results show that for a daytime load scenario in the range 33 to 95 kWh/d with an average of 76 kWh/d, a 15 kWp PV array can be used to displace at least 99% of all the daytime electrical loads including cooling loads. However, the economic analysis indicates that without support mechanisms, the longer payback period for the PV system may hinder the uptake of rooftop PV integration in Saudi residential sector.

Keywords: Rooftop PV, displacing cooling load, net metering, payback period, return on investment

1. Introduction

Residential buildings in the Kingdom of Saudi Arabia (KSA) consume 46% of the total electrical demand of the country (KAPSARC 2018), and almost 70% of such consumption comes from cooling loads (Mujeebu and Alshamrani 2016). The persistent hot arid climate of the country combined with its growing per capita income and cheaper electricity tariff made KSA the third largest electrical cooling load consumer in the world (Al-Badi and AlMubarak 2019). KSA is one of the rich sunbelt countries with huge potential of deploying solar photovoltaic (PV) technologies to sustainably transition its fossil fuel dominated electricity sector to low

carbon based on renewable energy. Despite such solar resources potential, in the electricity sector, PV only contributes about 433 GWh compared to 385,100 GWh by oil and natural gas in 2019 (Figure 1). Furthermore, KSA's per capita electricity consumption has been increasing annually reaching over 10 MWh in 2019 (Figure 1) (IEA 2020). To meet Saudi government's new renewable energy target of 27.3 GW by 2023 and 57.8 GW by 2030, as part of its 'Vision 2030' strategy, solar photovoltaics could play a vital role (Climate Action Tracker, 2020).

Integration of domestic rooftop PV would bring power directly to where it is consumed, in contrast to large



Fig. 1: Electricity generation by source in Saudi Arabia between 1990 and 2019, and growth in per capita electricity consumption during this period (Adapted from IEA 2020)

solar farms located outside cities. As the year-round residential peak cooling demands in Saudi residential sector are spread over the period between 11am and 5pm (Alshahrani and Boait 2018), this can be supported
by the PV power generated during this period without having the need for any expensive energy storage. This approach offers a great potential for Saudi housing sector to embrace PV power generation for self-consumption to displace cooling loads.

This work investigates how residential rooftop PV can support reducing grid-based air conditioning loads of a monitored case study building in Jeddah. The research presented here addresses the growth of rooftop PV supported by financial incentive tools in Europe and current policy frameworks for such PV systems in Saudi Arabia in Section 2, followed by the description of the methodology applied here (Section 3), the results and discussions in Section 4 and conclusions in Section 5.

2. Rooftop PV to support domestic loads

Global rooftop solar PV market size reached a value of USD 66.84 billion in 2019, and its installed capacity share recorded almost 13% of total PV installed in 2021 (IEA 2021). Residential rooftop PV for selfconsumption and exporting any excess power generation to the utility grid has been promoted in many countries since late 1980. Many countries in Europe (e.g. Germany, Denmark, Spain, Italy) were the early adaptors of lucrative `feed in tariff'(FiT) to enhance the uptake of residential PV dissemination (González 2008, Munksgaard and Morthorst 2008, and Deutsche Bank 2011). While the UK had seen the successful uptake of rooftop PV installation driven by FiT in 2008, France and Italy witnessed the highest growth in this sector in 2011 and 2012 respectively (Zhang et al., 2016). Besides, having a suitable FiT in place, appropriate policy framework is crucial to support the target dissemination of residential rooftop PV in any country. Through appropriate policy support and FiT, the UK for example had installed residential PV which generated 3.5TWh of electricity in 2016 (OFGEM 2017). While the FiT scheme in the UK ended in 2019, the Smart Export Guarantee (SEG), a government supported scheme was launched on 1 January 2020 to support such residential micro generations (OFGEM 2020). Applicable tariff for the electricity exported to the grid by the residential PV system under the SEG scheme varies with different energy supplier (licensee) of that residential customer (OFGEM 2019). According to Solar Energy UK (2021), SEG tariff varies from USD 0.021/kWh (offered by EDF Energy) to USD 0.15/kWh (offered by Tesla Energy through Octopus Energy provided that customers use Tesla Powerwall battery as storage).

2.1 Rooftop PV in Saudi Arabia

In 2017, a study on utilising the roofs of buildings in KSA has shown that, for the 13 cities considered, an annual combined potential of 51TWh from rooftop PV is feasible. This translates to about 30% of the domestic electricity demand (Khan et al., 2017). However, to date installed PV capacity in Saudi housing sector is negligible. To boost residential rooftop PV utilisation at a scale the Electricity and Co-generation Regulatory Authority (ECRA) in Saudi Arabia updated its Regulatory Framework for Small Scale Solar PV Systems in 2019 (ECRA 2019). Under this framework, PV systems with capacities between 1kWp and 2MWp are eligible to be connected to the utility grid through the local distribution service provider (DSP) under the following key terms:

- (i) DSP shall provide the net metering to the eligible residential customers provided that the aggregated capacity of small-scale solar PV to be connected to the utility grid shall not exceed 3% of the preceding year's peak load of the power system within its distribution operating area, and shall not exceed 15% of the rated capacity of the distribution transformer from which the load of the consumer is fed.
- (ii) In the case of large residential buildings (e.g. villas), which may have multiple meters, net metering arrangement by the DSP shall be done at one exit point linked to only one single meter, not to several consumption meters.
- (iii) While, under the current ECRA residential customer tariff slabs, customers with monthly consumption less than 6 MWh pay USD 0.048/kWh, and customers consuming 6 MWh or more each month pay USD 0.08/kWh (ECRA 2018), any eligible customer will get paid USD 0.02/kWh as feed in tariff (FiT) for any extra electricity generated and exported to the utility grid by the PV system regardless of their monthly consumption volume.

Stated cap on maximum installed PV capacity limits related to different DSP network areas by the ECRA's regulation may discourage potential early adaptors in installing bigger capacity PV systems. As the residential electricity tariff is cheaper in Saudi Arabia and it is well below the international market level (Aldubyan and Gasim 2021), residential customers may not be motivated to invest into rooftop solar. It is therefore, very important to analyse the suitability of such distributed generation under the policy and regulations and identify the challenges to inform the policy makers.

3. Methods

Installation of residential rooftop PV to support household loads in full or partially is a well-accepted technology application for using solar resources across the world, and the technology itself is well matured. However, uptake of such residential PV systems at national level depend on several interrelated factors, such

as: (i) applicability of the technology at local context, (ii) financial attractiveness (i.e., incentive, subsidy, feed in tariff) (iii) policy support and effectiveness, and (iv) awareness (Ahang et al., 2014, Zeineb et al 2015, Mundaca and Samahita 2020, Linda et al. 2020).

To investigate the potential of residential rooftop PV in reducing domestic air conditioning loads in Saudi Arabia, a methodological framework depicted in Figure 2 was developed. This framework embeds real data on consumption from a



embeds real data on consumption from a Fig. 2: Methodological framework for studying the potential of rooftop PV case study building in Jeddah. The data in reducing electrical cooling loads in Saudi residential sector

gathered through deployed monitoring systems underpins the PV system modelling and analysis and the techno-economic assessment based on existing policy regime in KSA.

The overall steps followed in the methodology to arrive at the system and economic recommendations are presented in Figure 3.



Fig. 3: Sequential steps of the study to investigate the potential of rooftop PV in reducing air conditioning electrical demands in Saudi housing sector

Electricity consumption data of the villa in Jeddah which consist of three floors with separate meters were remotely monitored for over a year with data captured at \sim 30 sec resolutions to understand daily and seasonal variations in loads. Here we only consider the 1st floor energy consumption data to model appropriate PV system, as this floor presents the main living area of 300 m² and highest cooling loads among three floors of the villa. The consumption data of this floor is termed 'study consumption' in the rest of the paper.

Simulations were carried out using a modelling software (HOMER Grid) to determine, (a) the ability of different PV system sizes that can support the air-conditioning loads only, and (b) how much the designed PV system could contribute to other loads, for the study consumption (first floor only). The optimum PV system is derived through the modelling, and an appropriate design of the system was developed so that it can be integrated to the existing electrical wiring of the villa. In addition, an economic assessment of the cost of installation for financial feasibility study of the proposed PV system was also carried out through the modelling based on the market cost of PV system components taking into account of the current Electricity Cogeneration and Regulatory Authority's (ECRA) policy and regulatory framework for small scale solar PV systems. For

the economic analysis of the final designs of the PV system, it was assumed that no interest to be paid on the initial investment. However, a fixed amount of USD 3000 for replacement and maintenance was included in estimating the potential savings on electricity bills over 25 years of the PV system's operational life. Based on the combined outcomes of the techno-economic analysis appropriate policy and financing recommendations are made to support the utilisation of rooftop PV in KSA.

4. Results and discussions

In the study consumption case (1st floor of the villa) the electrical loads varied between 66 kWh in February and 167 kWh in June, with May and July presenting almost similar average daily load of 150 kWh (Figure 4). Total daily (day and night) electricity consumption (i.e. cooling, lighting, hot water, entertainment, other) and the daytime only consumption of the 1st floor of the villa at different months of the year showed similar pattern in load variation (Figure 5). This is due to the fact that cooling loads dominate the electricity consumption of this floor. While daily (day and night) AC (cooling) loads varied between 46kWh/d in February and 117 kWh in June, daily daytime only AC (cooling) loads varied from 24.5kWh in February to 64kWh in June (Figure 5).



Fig. 4: Hourly average electrical loads (kW) for the study consumption (1st floor of the villa) for six months representing three highest and three lowest months

Table 1 shows the annual data for the monitored electrical demand for the 1^{st} floor (study consumption) indicating a total daily (day and night) load of 39.4 MWh/y, daytime only total load of 23.1 MWh/y, daily cooling load of 29 MWh/y and daytime only cooling load of 16 MWh/y. This indicates that the evening load is about 16.3 MWh/y (=39.4 - 23.1). According to ECRA, the tariff for this residential customers is USD 0.048/kWh as the study consumption (1^{st} floor) load is below the 6 MWh/m threshold (Table 1) (ECRA 2018).

Figure 6 presents the efficacy of different size of grid connected PV systems modelled to serve various load scenarios of the study consumption without energy storage. The results show that modelled PV systems below the capacity of 10 kWp were able to serve \leq 50% of daytime loads, and significant shortfalls in serving cooling loads were evident in this range (Figure 6). However, the modelled 15 kWp PV system outperformed its close capacity options of 14 kWp and 17 kWp as it is able to serve 99% of the total daytime loads as



Fig. 5: Average daily electrical loads (total load, total cooling load, total daytime only loads and total daytime only cooling loads for the study consumption (1st floor of the villa)

 Table. 1: Yearly electricity consumptions of the study

 consumption (1st floor). For this range the applicable

 consumption tariff is USD 0.048/kWh

-	
Load type	Load
Total daily load	39.4 MWh/y
Daytime only total load	23.1 MWh/y
Daily cooling load	29 MWh/y
Daytime only cooling load	16 MWh/y



Fig. 6: Efficacy of different size of PV systems serving the total load including air conditioning loads for the study consumption case.

well as full daytime cooling loads. Therefore, the 15 kWp PV system is considered as the optimum system size to fully support the study consumption (1st floor of the villa).

Figure 7 shows the results of the seasonal variation in power generation by the 15 kWp PV system in comparison to the variations in total electrical loads of the study consumption (1st floor). With the annual PV power generation of 27.2 MWh, the 1st floor of the villa (study consumption) needs to import 12.2 MWh each year from the utility grid to meet the total demand of 39.4 MWh/y (Figure 7). As the daytime only load is 23.1 MWh/y (Table 1) and the PV system does not have any energy storage, the excess amount of 4.1 MWh/y energy is exported to the grid.

Under the current net metering provision of ECRA, if the 1st floor of the villa (study consumption) is billed on a monthly cycle, the villa consumer will pay USD 0.048/kWh for the amount of electricity it imports from the grid, and will get paid USD 0.02/kWh for the excess power it exports to the grid by the 15 kWp PV for the months it remains as net exporter.

Based on the structure of the roof, its layout and available shadow-free area, a 15 kWp gravity mount grid connected three phase PV system is designed which can be integrated into the existing electrical wiring of the household (Figure 8). The cost of the system including installation was estimated to be USD 17,500 (Table 2).

Considering the yearly daytime electrical demand (23.1MWh; Table 1) served by the 15 kWp PV at an import tariff of USD 0.048/kWh, and total energy exported to the grid (4.1MWh/y) at an export rate of USD 0.02/kWh, the study consumption (1st floor) saves ~USD 1180 ((23MWh/y x USD 0.048/kWh = ~USD1100) + $(4.1 \text{MWh/y x USD } 0.02.\text{kWh} = \sim \text{USD80}))$ each year on its electricity bill. Without having the rooftop PV installed, this household would have paid electricity bill of USD 1890/y (39.4MWh x USD 0.048/kWh). Therefore, with the proposed 15 kWp PV system installed, this villa will have a yearly electricity charge of USD 710 (=1890-1180) for the study consumption to serve its total demand of 39.4 MWh/y.

Figure 9 presents estimated payback period for the 15 kWp PV system for the study consumption (1st floor) load scenario based on the electricity bill savings (USD 1180/y) as indicated above. The figure also shows the amount of savings on electricity bill over the life of the project. Under the current applicable electricity tariff (USD 0.048/kWh) of the study consumption (1st floor), where total cost of the proposed PV system (USD



Fig. 7: Seasonal variations in power generation by the proposed 15kWp PV system in comparison to the total electrical demand variation of the study consumption (1st floor) during the similar periods of the year.



Fig. 8: Architecture and components of a 15kWp grid connected PV system for the study consumption

Table. 2: Estimated cost (components and installation) of the 15kWp three phase grid connected PV system for the study consumption (1st floor of the villa). *PV system life 25 years*.

Item	Cost (USD)
PV 370Wp each x 40 panels	7200
Inverter 15kW (grid tie, 3 phase)	2500
DC Switch gears & cables	1600
AC Switch gears & cables	1400
Gravity mount & structure	3000
Permission, installation & metering	1800
Replacement & maintenance cost	3000
Total cost of the system	17500



Fig. 9: Cost of electricity for the study consumption (1st floor) with and without the 15kWp PV system installed over 25 years.

17500) is paid upfront (0% interest), it recovers the investment in the 16th year. Furthermore, in such investment scenario, the amount of savings over 25 years is ~USD 10,000 (Figure 9). If an interest rate of 4% is considered on the investment of the PV system assuming USD 17500 to be repaid in 5 years, recovery of the cost defers to 18th year. The saving over the life of the project, in this case is reduced to ~USD8000 (Figure 9).

The estimated payback period of 16 years for the proposed 15 kWp PV system in the case of the study consumption (1st floor) load is considerably too long to encourage residential customers to invest in such rooftop PV systems.

However, such PV interventions are likely to make the investment worthwhile especially for large consumers. For the case of a residential customer with monthly consumption of 6 MWh or higher, the day time load will be larger than the study consumption (1st floor) and all power generated by the same proposed PV system will be self-consumed by the customer leaving no export to grid. The import tariff for such customer is USD 0.08/kWh, which translates into an electricity bill savings of ~USD 2175/y (27.2MWh/y load served by the PV system x USD 0.08/kWh consumption tariff) and the payback period for proposed 15 kWp PV system is around 8 years considering no interest on investment. The total savings over 25years in such case is ~USD 34000 (($$2175 \times 25y$) – (Investment = \$17500 + \$3000 for O&M and replacement 13th year)).

Payback period for the proposed 15 kWp PV system for the larger consumer (import tariff at USD 0.08/kWh) mentioned above is halved when compared with the study consumption case where the import tariff USD is 0.048/kWh. This means that under the current consumption and feed in tariff regime, rooftop PV installation will be more attractive to the higher electricity consuming customers.

5. Conclusion

The Kingdom of Saudi Arabia (KSA) is one of the rich sunbelt countries with very large solar resource, appropriate for solar photovoltaic energy conversion deployment. This is important at the housing level, where the hot arid climate of the country combined with its growing per capita income and cheaper electricity tariff is driving electrical cooling demand resulting in the country having the 3rd largest cooling load consumption in the world. Intervention of PV power generation at the housing level has many advantages, including reduced transmission losses, but more importantly bringing power generation at the point of use (Bahaj and James 2007).

Hence, in order to address such cooling loads at the residential housing level, this work presented an investigation in identifying appropriately sized residential rooftop PV systems that can reduce such loads under the weather conditions of KSA. Furthermore, the presented results were based on real data obtained through yearly monitoring of the electrical consumption of different floors of a case study villa in Jeddah. The modelling identified an optimum design of 15 kWp PV system that can serve 99% of the annual daytime loads including cooling of the villa represented by the 1st floor. The designed system was also capable of contributing additional power to support other daytime loads in the villa. Increasing the size of PV system to greater than 15 kWp would have resulted in oversizing the system under the current applicable import tariff of USD 0.048/kWh and feed in tariff of USD 0.02/kWh if an energy storage system is not used. On the other hand, adding energy storage to the PV system would increase the cost, and financially the system may not be viable.

The results show that a payback period for such a system and considered load is of the order of 16 years, which is too long to encourage residential customers to invest in such systems. However, for large consumers such interventions are likely to make an investment worthwhile especially for the higher import tariff of USD 0.08/kWh. This means that under the current consumption and feed in tariff regime, rooftop PV installation will be more attractive to the higher electricity consuming customers. Nevertheless, it is anticipated that the import tariffs will rise year-on-year and some form of incentives will be announced in KSA in the near future. This is likely to scale up the utilisation of PV on buildings in KSA.

6. Acknowledgement

This work is part of the activities of the Energy and Climate Change Division (ECCD) and the Sustainable Energy Research Group (SERG) in the Faculty of Engineering and Applied Sciences at the University of Southampton (www.energy.soton.ac.uk), UK, and the Department of Electrical and Computer Engineering,

King Abdulaziz University (KAU), Saudi Arabia. The work is funded by the Ministry of Education in Saudi Arabia through project number 714, coordinated through the Deputyship for Research and Innovation, KAU.

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M-06. Methods and Tools (to analyse the design of solar buildings and/or neighborhoods)

Glare Hazard Analysis of Novel BIPV Module Technologies

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Abstract

Standard Photovoltaic (PV) modules use anti-reflective (AR) surfaces or coating to maximise solar energy transmission and minimise reflection (Hartmeyer, 2019). Despite this, they can still create glare hazards. New PV modules have been developed for building-integrated photovoltaics (BIPV) to lessen the possibility of glare hazards. In this paper, an outdoor measurement technique for evaluating glare hazards of PV modules is introduced. Eight different PV module glass technologies and coating technologies are tested and compared. The results show that by reducing specular reflection and increasing beam spread, the relevant measure of glare (luminance) can fall by several orders of magnitude without reducing the performance of the PV modules.

Keywords: glare hazard, beam spread, luminance, specular and diffuse reflection, PV modules, solar glass

1. Introduction

Glare hazards caused by PV modules can be a relevant issue, primarily for circumstances where PV systems are built in the vicinity of airports (Ho et al., 2015). Although, several instances of PV systems built close to runways succeed in not increasing safety risks for aeroplanes. Glare hazards are also relevant in neighbourhood areas. Swissolar, the Swiss PV association, reports an increasing number of neighbour disputes due to glare effects from PV systems. South-facing PV systems in the northern hemisphere are normally not critical. East and west-facing systems can cause glare hazards to neighbours east and west of the system, mainly shortly after sunrise and before sunset. Though, due to the short duration of the glare hazard, these systems are also usually not too problematic. However, north-facing systems are often critical if neighbours are located north of the PV system.

In Switzerland, there have been various court cases dealing with glare (Bohren, 2015 and Stickelberger, 2021). One of the difficulties is that the law knows neither limits for glare duration nor glare intensity. Therefore, case law on these matters is unpredictable.

In various older publications, the terms 'glare' and 'reflection' are not clearly distinguished (Shields 2010, Shea 2012). In the Swiss 'Raumplanungsverordnung' (RPV 2021), PV systems must be designed with low reflection according to "state-of-the-art" to avoid the need for a building permit. Consequently, a conflict arises: while most PV modules are optimised for low reflections (e.g., through using AR coating), only a few are designed for low glare. AR coated modules will not necessarily reduce glare hazard risks but could increase them (Ruesch 2015).

This paper gives relevant definitions of glare hazards and related terms (see chapter "2. Fundamentals of Glare Hazards"). Additionally, an outdoor measurement procedure is investigated to evaluate the glare potential of single PV modules and entire PV systems (see chapter "3. Methods to Measure Glare"). The method is tested using different module technologies and different measurement distances.

The measurement results of three PV module types, available on the market, and five prototypes are presented and evaluated. Mathematical functions to characterise the glare properties of these modules are proposed.

2. Fundamentals of Glare Hazards

2.1 Literature review on glare hazards

In DIN EN 12665:2018, glare is defined as an uncomfortable visual condition due to unfavourable luminance distribution or excessive contrast. However, no limit values are given. In Wittlich (2010), a differentiation between absolute glare and relative glare is made. *Relative glare* is mainly based on high contrasts, while *absolute glare* is defined as the saturation of the eye, which occurs between luminance values between 10'000 cd/m² and 1'600'000 cd/m² (Wittlich, 2010).

In the SGHAT tool derived in Ho (2011, 2015), the relevant measure for glare is given by the retinal irradiance in W/cm^2 and by the subtended source angle in mrad. The larger the subtended source angle, the smaller the retinal irradiance limit for *potential for after image* or even *retinal burn*, according to SGHAT.

Luminance in cd/m^2 indicates how bright a surface is from the point of view of an observer. The relevant measure used in this paper is luminance in cd/m^2 (Wittlich, 2010, Ruesch 2015). Measurements carried out by the authors of this paper show that the highest luminance levels for diffuse reflectors (a white wall in the sun) are in the range of 20'000 to 30'000 cd/m². Similar results have been found in Ruesch (2015).

2.2 Definitions used in this paper

Due to the unclear nature of the definitions and limits for glare given in the literature and legal documents, the following definitions are used:

- Glare is defined as a disturbing reflection.
- Glare occurs if the luminance of a reflection is $> 50'000 100'000 \text{ cd/m}^2$.

Note: the above definitions may only be appropriate in the context of this paper and not as general definitions for the terms.

The second value is chosen based on the literature research and the authors' experience in the measurements carried out for this paper. While $25'000 \text{ cd/m}^2$ in a bright environment does not necessarily cause glare, reflective surfaces of $100'000 \text{ cd/m}^2$ and more appear too bright to look directly into, even if the eye gets momentarily adjusted to a bright environment.

2.3 Glare hazards on PV systems compared to other glare hazards

Glare hazards can occur in many built-up environments and on various surfaces, but the severity differs in some aspects from glare hazards on PV modules:

- Since PV systems typically cover large areas, glare hazards can last a long time. Severe glare hazards can last for several hours a day. Whereas in built-up environments, the glare hazards of other surfaces such as roof windows usually last only a few minutes.
- For the same reason, it is difficult to avoid the beam of glare once it occurs. While the beam of glare from a conventional roof window glass is limited to about one or two square meters, the beam of glare from PV systems can affect a whole sitting area or garden.
- On the other hand, glare hazards on PV systems are often much weaker than glare hazards on other surfaces such as conventional window glass.

Fig. 1 gives an overview of several surfaces and their luminance.



109

10⁶

10³

1

10-3

10-



The luminance of a reflecting surface does not primarily depend on its reflection coefficient but the specularity of the reflection. Assuming that a mat, white surface with a reflection coefficient of 1.0 does not cause any glare due to its diffuse reflection behaviour, only specular or partly specular reflection cause glare hazards (see Fig. 2).

To reduce the glare properties of a surface, it is not necessary to reduce the reflection. The glare properties of a surface can decrease by widening the reflection beam (beam spread). The PV modules tested in this paper (which cannot cause glare hazards unless in specific situations) have relevant beam widening properties.



Fig. 2: Effect of beam spread on the luminance of a PV module.

3. Methods to Measure Glare

3.1 Indoor laboratory measurement of glare

A precise way to measure the reflection properties of surfaces is described in Ruesch (2016). The Bidirectional Reflection Distribution Function (BRDF) describes the reflecting luminance of a surface as a function of all possible angles of incidence, reflection angles and the illuminance in Lux. To measure the BRDF, the surface in question is illuminated with a light beam under all relevant angles. The reflection is captured using a hemispheric screen, and a camera is used to measure the screen's luminance.

The BRDF gives a holistic picture of the reflection properties of a surface such as a PV module. However, it is neither possible nor necessary to measure a BRDF of a whole PV installation. For this purpose, on-site glare measurements using a luminance meter or camera is more suitable.

3.2 On-site measurement of glare

On-site measurements are done during the glare period under clear-sky conditions. The results are not as holistic as the BRDF laboratory measurements and less accurate and repeatable, but they provide two main advantages:

- No changes/manipulations at the PV system are necessary.
- The measurement setup and results capture exactly the situation which is visible at the observation point.

In this paper, an on-site measurement method to measure the possible glare of a PV system is investigated. The precision of the measurement method is estimated using an outdoor laboratory setup.

Measurement devices

The following measurement devices are used in this paper:

- Gossen MAVO SPOT 2 USB: luminance meter
- ND1000 Neutral Density Filter: lowers luminance by a factor of 1000



Fig. 3: Calibrated luminance measurement device MAVO SPOT 2 used for glare measurements (left). View through the lens of MAVO SPOT 2 (right). The circle in the centre of the measurement spot covers an angle of 1°.

Independence of Distance

The reflection of the busbars of a PV module can falsify the measurement results. The reflection due to the busbar occurs when the distance between the measurement device and the module is too small, causing the busbar to occupy a big amount of the measurement field of 1°. The negative effect increases if the glass under examination shows a comparatively low luminance, which results in a higher dominance of the busbar's reflection. Fig. 2 shows that the variability of measurement results decrease a lot if the distance between the measurement device and the module is 2 meters or more (green area).



Fig. 4: The luminance measurement is inherently subject to relatively large variance. However, the variance increases a lot when the distance between the measurement device and the module under test becomes too short and only a single busbar is within the measurement area of the luminance measurement device (red area). Left: incident angle = 10°. Right: incident angle = 45°.

The module that showed the lowest luminance (satinated glass) is examined to determine the minimum required measurement distance. If the busbars show no relevant reflection at a certain distance, their influence is even lower for glasses with more specular reflection properties.

The measurement results show maximum values around 7000 cd/m^2 at distances of 2 m and larger. At shorter distances, some values are a lot higher due to the dominance of the reflections of the busbars.

It is proposed to cover at least two busbars with the measurement device to minimise their dominance, as shown in Fig. 5.



Fig. 5: If the measurement captures at least two busbars, the busbars will no longer falsify the measurement.

Distribution of measured values

Due to inhomogeneities in the luminance of the module surfaces and due to the manual measurement procedure, the luminance measurements are subject to a lot of noise and outliers. Misalignment of the measurement device, which cannot be avoided in practice, leads to big measurement deviations. Therefore, raw data is filtered with the following outlier detection algorithm:

data used	$> Q_{65}$	(1)
outliers	all other data	

where Q_{65} is the 65% quantile of the data. The quantiles are calculated using 10 values before and 10 values after the given luminance values (sliding quantiles). The single-sided filter was chosen because all outliers have lower values than the expected values. The results of the data filtering process are shown in Fig. 2.



Fig. 6: Raw data from the luminance measurements of all PV modules (left) and the standard PV module only (right). Outliers are marked in red.

3.3 Empirical function to describe the glare behaviour of PV modules

To describe the measurements, the following functions are proposed. The functions fit the common logarithm (\log_{10}) of the luminance:

$$y_1 = a \cdot x^4 + b \cdot x^2 + c \tag{2}$$

 $y_2 = b \cdot x^2 + c \tag{3}$

$$y_3 = spline \tag{4}$$

 y_1 is a symmetrical fourth-degree polynomial function (biquadratic) and y_2 is a symmetrical square function (quadratic). These functions were chosen because they are symmetrical and have similar shapes to the measurement data. The vertex is at x=0. y_3 is a natural cubic spline with two internal knots. Due to the high number of adjustable parameters y_3 is assumed to give the best possible fit. y_3 is therefore used as the benchmark for the highest expected coefficient of determination R². y_1 and y_2 are relatively simple functions having only 3 and 2 parameters, which is less accurate but beneficial for the practical use of the equations.

The quality of the fit measured by the R^2 varies a lot for different measurements. The biquadratic function is beneficial for some measured curves but not for all. Fig. 7 shows the fit for a standard PV module and a satinated module as two examples. For the satinated module, the coefficient of determination of the biquadratic equation is clearly better than that of the quadratic equation.



Fig. 7: Quality of fit depending on the module technology. Left: Standard PV module. Right: Satinated PV module.

4. Results

4.1 Comparison of different solar modules

The luminance measurement results of all tested PV modules are shown in Fig. 8. The parameters found for the measurements and their coefficient of determination are given in Tab. 1. The coefficients of determination are compared in Fig. 9.

Generally, both the quadratic and the biquadratic functions are suitable to model the luminance data of the various PV modules.



Fig. 8: Luminance measurement result of different PV modules including best fit functions.

	$y_1 = a \cdot x^4 + b \cdot x^2 + c$					$y_2 = b \cdot x^2 + c$			spline	
Name	a	b	c	R ²		b	c	R ²	R ²	
Deflect	3.69E-08	5.70E-05	4.20	0.981		3.22E-04	3.99	0.935	0.988	
Float	1.16E-08	2.75E-05	7.25	0.966		1.10E-04	7.17	0.919	0.97	
Float Coated	2.83E-08	1.14E-05	7.15	0.808		1.56E-04	7.06	0.753	0.85	
Foil 1	-2.14E-08	2.88E-04	3.97	0.565		1.99E-04	4.01	0.551	0.628	
Foil 2	1.10E-09	2.05E-04	4.23	0.865		2.12E-04	4.23	0.865	0.88′	
Satinated	2.80E-08	1.23E-05	3.69	0.873		2.03E-04	3.53	0.819	0.900	
Standard	-2.33E-11	3.53E-04	5.73	0.980	1	3.53E-04	5.73	0.980	0.98′	
Standard Coated	2.22E-09	3.29E-04	5.35	0.906		3.40E-04	5.35	0.906	0.91	

Tab. 1: Parameters derived for the functions in Fig. 8.



Fig. 9: Coefficient of determination R² values for the functions fitted to the data.

4.2 Case study: Replacement of standard PV modules with satinated PV modules

A north-facing roof-integrated PV system with PV modules made of standard solar glass caused glare effects on the neighbouring garden and living room. The glare effects were quantified for several weeks in summer and up to 2.5 hours per day.

The luminance of the PV modules, installed in 2016, was measured on-site by the BFH PV laboratory on a cloudless day in June 2021. In a test setup, four of the modules have been replaced by satinated PV modules. The measured luminance values are reduced by a factor of around 1000 and are well below the limit of 50'000 - 100'000 cd/m² mentioned in chapter "2 Fundamentals of Glare Hazards" (Fig. 10).

The appearance of the old and the new PV modules are shown in Fig. 11. It can be concluded that the satinated PV modules eliminated the glare hazards.



Fig. 10: Measurements of the reflected beam from the roof window, the standard PV module, the new satinated PV modules and the standard PV module out of the reflected beam.



Fig. 11: Roof-integrated PV system with standard solar glass modules (left), four satinated modules for testing purposes (middle) and fully covered with new satinated PV modules (right).

5. Conclusion and Outlook

Two main conclusions can be drawn from this paper:

- 1. The glare potential of different PV modules largely varies. New module surface technologies such as satinated glass or glass coated with a foil can reduce or even eliminate the risk for glare hazards.
- 2. The luminance of module surfaces can be measured in the laboratory or on-site. Outdoor measurement results are subject to high level of noise. Filtering the data increases the data quality and makes it possible to present the results in a simple quadratic or biquadratic form.

The measurement results in this paper do not yet fully explain the phenomenon of glare. The reproducibility and reliability of the measurement method must be further investigated and proven in future research projects.

Since these anti-glare modules are relatively new on the market and only little experience with glare measurements is reported, some research is still required to fully understand their possibilities and limitations. Hence future research questions are:

- How robust is the outdoor measurement procedure regarding meteorological influences? What are minimum requirements for both the measurement procedure and the meteorological conditions during the measurements?
- How do the outdoor measurement results correlate with BRDF measurements done in the laboratory? The BRDF gives one 3 dimensional function for every angle of incidence, whereas the method presented in this paper limits the reflection characterisation to one dimension only (one number for every angle of incidence). What is the error which has to be expected with this method?
- Are the proposed functions for describing glare properties generally valid for all possible PV modules?

And are they useful to characterise PV modules in terms of their glare properties?

How do the optical properties of anti-glare modules change over time?

6. Acknowledgments

The authors acknowledge the project support oft Swissolar and the Swiss Federal Office of Energy (SFOE) as well as the Institut für Solartechnik (SPF) of the Eastern Switzerland University of Applied Sciences (OST) for the collaboration.

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Selection of Weather Files and Their Importance for Building Performance Simulations in the Light of Climate Change and Urban Heat Islands

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Abstract

Building performance predictions and their reliability rely heavily on weather data inputs. Climate is affected by spatial and temporal differences related to climate change and urban heat island effects, but the weather files used in building performance simulations (BPS) often remain unchanged and may represent weather observations generated from inadequate space and time for their application. This study investigated Swedish weather data using statistical methods and analysed i) the local differences related to rural and urban microclimates and ii) the country-wide differences linked to climate change; by comparing recent observation data to the respective EnergyPlus Weather (EPW) files. The findings reveal that there are significant differences between rural and urban temperature means, and that outdated model years of weather data files make them unsuitable for BPS. The impact of using an inadequate weather file based on changes in recent climate in Sweden can lead to an overestimation of heating demand by 6.5 % on average, while the impact is higher for warmer climates – up to 12 %. The combined impact including climate change and urban heat island effects can lead to a heating energy overestimation by 12 % to 19 %, based on the Stockholm example. On the other hand, it was found that although the global radiation means saw a slightly increasing trend, its impact on the BPS remains inconclusive. The study highlights the importance of selection of adequate weather data for BPS keeping in mind the spatial and temporal influencing factors.

Keywords: weather data, EPW, statistical analysis, urban heat island, climate change, building performance simulations

1. Introduction

Weather data is a central input in building performance simulations (BPS) and sustainable urban planning. It defines the output of simulations relating to daylighting, energy use, and solar potential, and ultimately influences the decision-making process in the urban planning and building design practice. In a typical BPS process, a weather file selection is fixed to a single available weather file which is used repetitively in studies of a given geographical or administrative area and contains hourly values representing a typical meteorological year (TMY). One of the common weather file extensions used in building simulation software based on EnergyPlus and Radiance is the EPW (EnergyPlus Weather) file format. International EnergyPlus database is a large repository of EPW files from many different weather sources (EnergyPlus, 2021). It is often not possible to pick and choose between different weather files for a given location; there is usually only one that is the nearest available hence deemed the most suitable. For some locations and some data repositories it may also be difficult to obtain files with updated TMY with observation from the most recent years. In other terms, available weather file might not be fully representative due to spatial (location of the weather station) and temporal (years of observation included in the TMY) differences.

There are two key factors that drive the local spatial and temporal, as well as short-term and long-term, weather observation differences: urban heat island and climate change. Their effects on BPS have been previously studied, see e.g., (Burleyson et al., 2018; Crawl, 2008; de Wilde and Coley, 2012; Moazami et al., 2019). Studies also investigated the impact of future climate scenarios on BPS (Baglivo et al., 2022; de Masi et al., 2021; Moazami et al., 2019). Nik and Sasic Kalagasidis (2013) showed that the heating demand of Stockholm's residential buildings might expect a potential decrease of 30 % under a future climate scenario. On the other hand, a study by Guattari et al. (2018) investigating urban climate of Rome demonstrated that the average cooling need was 30 % higher, pertaining to urban heat island effects alone.

The urban heat island effect drives climate differences on a local scale. The phenomenon occurs due to conducive urban characteristics such as high build-up density, scarce vegetation, thermal waste, and the extensive use of heat-

© 2021. The Authors. Published by International Solar Energy Society Selection and/or peer review under responsibility of Scientific Committee doi:10.18086/swc.2021.46.02 Available at http://proceedings.ises.org

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storing materials and dark surface colours; all of which causes the city centres to reach higher ambient and radiant temperatures, meanwhile possessing a decreased ability for radiative cooling due to a limited openness to the sky. Since the weather files are commonly built from stations located outside of the cities e.g., at rural airports, they typically do not account for this effect. In Sweden, six city locations are covered by the EnergyPlus database of EPW files, five of which come from rural airport-based weather stations outside of the city (Table 1). The source of the presented Swedish weather data files is IWEC (International Weather for Energy Calculations), which was developed by ASHRAE (ASHRAE, 2001).

City and weather file name	Weather station location	TMY time period
Copenhagen (DK; also used in Malmö, SE)	Kastrup Airport	1983 to 1999
Gothenburg (SE)	Landvetter Airport	1983 to 1995
Karlstad (SE)	Sommarro area	1984 to 1996
Kiruna (SE)	Kiruna Airport	1982 to 1993
Östersund (SE)	Åre (Frösön) Airport	1982 to 1999
Stockholm (SE)	Arlanda Airport	1984 to 1993

Table 1. The available Swedish EPW file locations and the observation time spans they are generated from.

While the heat island phenomenon triggers spatial microclimate differences, climate change alters the long-term weather patterns. The available EPW files in Sweden contain data based on real weather observations taken within a similar time span, ranging from 1982 to 1999, as shown in Table 1. Climate change is affecting locations globally in varying magnitudes, and it is important to understand how different places around the world are impacted. While future climate scenarios were previously applied in BPS studies in Sweden (Moazami et al., 2019; Nik and Sasic Kalagasidis, 2013), the disparities between recent weather observations and common Swedish weather files have not yet been studied.

To investigate the impact of the selection of weather files, a statistical analysis of Swedish weather data was conducted. The main objective of the research was to study the differences between the EPW weather data sets and recent weather observations, which might adversely impact future solar and thermal building performance predictions. The goal was to investigate firstly, whether there are significant statistical differences between the rural and the urban weather observations based on Stockholm's urban agglomeration, and secondly, whether the available EPW files for Swedish locations remain representative of the most recent weather patterns. The study looked at both hygrothermal as well as solar weather parameters (global radiation, sun duration) and analysed their potential impact on BPS. Since the impact of climate change on clouds is still largely unknown (Ceppi et al., 2017), it is important to study the solar aspects of climate. Lastly, the outcomes of the study address a key question for BPS: Is it important to continuously update the simulation weather files?

2. Methodology

2.1. Rural and urban differences - Stockholm

The first part of this study analysed dry bulb air temperature records measured in six selected stations located in Stockholm County. The analysis area was of a 35 km radius with Central Stockholm at its centre. The measured temperature data was obtained from SMHI (Sweden's Meteorological and Hydrological Institute) (SMHI, 2021a). Thirteen years of data records spanning between year 2008 and 2020 were extracted for the selected weather stations. The prerequisites for selecting suitable weather stations were: 1) the data was recorded hourly, 2) the station was active in years 2008-2020, and 3) the station was located in the Greater Stockholm area. The following weather stations were selected: Stockholm (A), Adelsö, Arlanda, Bromma, Tullinge, and Skarpö. To study their location on the map of Greater Stockholm area, see Figure 3. For each station and each annual hourly temperature data set, an annual temperature mean was calculated.

There were missing records in the retrieved data sets. Following the statistical significance level rule of 5 %, the annual data sets which had more than 5 % of data records missing were considered as significant loss of data and thus were removed from the analysis. There were four such data sets: Adelsö 2016, Arlanda 2008, and Skarpö 2014 and 2015.

A statistical analysis on the annual mean temperatures was conducted in RStudio (RStudio Team, 2021). A general

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linear model was used, and analysis of variance (ANOVA) as well as post hoc comparison tests (Tukey's method) were performed. Test assumptions regarding normality and homoscedasticity of the residuals were checked.

Weather data files used in BPS were introduced to assess their likeness to the measured data and to evaluate their ability to digitally represent the analysed climate of the recent time period in computer-based modelling. The weather data was obtained from two databases: EnergyPlus (EP) (EnergyPlus, 2021) with data source IWEC (ASHRAE, 2001), and OneBuilding (OB) (OneBuilding Climate, 2021). The former is a widespread source of weather data for BPS. Ladybug Tools (Ladybug Tools, 2021) users can connect directly via a web browser to a Ladybug interactive map providing many EP files to download, including IWEC files (Roudsari and Peng, 2021). As previously indicated, those files are often based on old measurements (Table 1). OB, on the other hand, is a free repository of TMY weather data that is updated continuously and covers many more locations. For this study, there was only one EP file available for the analysed area, while there were twelve different OB files – two for each of the stations, containing two different sets of model years on which the TMY data was based.

2.2. Spatial and temporal differences - Sweden

The second part of this study investigated weather data measurements from six Swedish locations: Stockholm, Gothenburg, Malmö, Östersund, Karlstad, and Kiruna (Fig. 1). The data was retrieved from SMHI's database (SMHI, 2021a), from weather stations that were located closest to the available IWEC weather file for a given city, and for eleven consecutive years: 2010-2020. The following weather parameters were analysed: air temperature (°C), relative humidity (%), global solar irradiance (W m⁻²), and sunlight duration as fraction of an hour. Annual averages from the measured hourly-based data were calculated: for temperature and humidity – taking all data items, and for irradiance and sunlight duration – taking only data for those hours when the sun is up, which differs per location. Additionally, yearly temperature extremes were also investigated.



Figure 1. Locations of the weather stations for the analysis of Swedish weather.

The sunlight duration parameter was accounted for differently in the measured data and in the weather file data. SMHI uses a threshold of above 120 W m⁻² in measured global radiation to determine that a given second was sunny (sunlight was present) and gives the results of these measurements hourly with maximum value of 3600 per hour (SMHI, 2021b). The SMHI sunlight duration data was normalised for this study, and all values were divided by the maximum to give a range between 0 and 1. The weather data from EPW files, on the other hand, provided information about the cloud coverage of the sky for every hour of the year, the invert of which was taken as sunlight duration.

There were some difficulties encountered during data extraction. Relative humidity data was missing or was of inadequate quality (category yellow by SMHI) for all locations for measurements in years 2010, 2011, 2012, and 2020: thus, only seven measurement years were considered for this parameter, except for Malmö where year 2020 records were available. Solar stations, those that measure global radiation and sunlight duration, were positioned in

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different locations than the weather stations which recorded the temperature and relative humidity; however, they were still located within the same precincts, except for Malmö, as the closest solar measuring station was in the nearby town of Lund.

Climatic differences between the selected Swedish locations but also differences between recent weather measurements and respective TMY data for these locations were investigated. The weather data files for all locations were sourced from EnergyPlus IWEC database. For Malmö, the Copenhagen file was used, as it was the nearest available location from IWEC.

Each parameter was first analysed separately using an additive linear model design. The assumptions for the ANOVA were checked for each data set. Temperature, relative humidity, and sun duration data sets proved normality and homoscedasticity on residuals; however, tests on radiation data set rejected the normality hypothesis. In order to be able to conduct further statistical tests, outliers of the radiation data were identified and removed. To ensure data normality, it was sufficient to remove just one radiation record, for Malmö 2017, which was the biggest outlier. ANOVA of every weather parameter data set showed that the locations and years had significant differences with high significance p-value levels. Post hoc comparisons were conducted on each weather parameter separately.

3. Results and discussion

3.1. Rural and urban differences - Stockholm

The annual temperature averages are shown in Figure 2. The parallel appearance of the lines indicated a block effect in the data; hence, a linear additive model with blocking was used. Next, one-way ANOVA was used to test whether the block design was appropriate. The ANOVA indicated that there was a significant (p<0.001) difference in the data corresponding to the year and the location, and that the grouping of data into blocks was adequate. The assumptions for ANOVA were tested using the Shapiro-Wilk and Levene tests, which did not reject normal distribution and homoscedasticity of the residuals, so the assumptions were met.



Figure 2. Interaction plot with Stockholm weather stations temperature means. Some lines appear broken because of missing data.

The Tukey's post hoc comparison test results with the level of significance $\alpha = 0.05$ are presented in Table 2. There are small standard errors and many degrees of freedom. The comparison of the location means showed that there are four groups of stations with significantly different temperature means, while three stations, Skarpö, Bromma, and Adelsö, did not have significantly different means according to the Tukey's test. The table also includes an annual temperature mean for the IWEC weather file from Stockholm Arlanda which was added to contrast the statistical means with the TMY mean.

Location	emmean (estimated marginal mean)	SE (standard error)	DF (degrees of freedom)	Lower CL (confidence level)	Upper CL	Group
Stockholm	8.12	0.0540	56	8.01	8.23	А
Skarpö	7.76	0.0597	56	7.64	7.88	В
Bromma	7.71	0.0540	56	7.60	7.82	В
Adelsö	7.59	0.0567	56	7.47	7.70	В
Arlanda	7.16	0.0567	56	7.05	7.27	С
Tullinge	6.76	0.0540	56	6.66	6.87	D
IWEC (Arlanda)	6.49					

Table 2. Tukey's post hoc test results with	n statistical grouping of means	(descending order)
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The weather station located in the Stockholm's city centre, named 'Stockholm', resulted in the highest estimated temperature mean. It was also significantly different from other stations. The result confirms the initial hypothesis that the air temperatures are higher in city centres, closer to the densely built and populated urban areas (Fig. 3), which might be ascribed to the known heat island effect.



Figure 3. Stockholm's weather stations and population density (source: Lantmäteriet).

Weather stations of Bromma, Skarpö, and Adelsö were placed together in one group, which was the second highest group by temperature means. This means that there is no significant difference between these station's temperature means. While Bromma was located close to the agglomeration's centre, the other two were located outside of the strict city centre. The reason the means are not different could be attributed to the geographical and topographical location of the two rural stations. Skarpö and Adelsö are located close to large sea reservoirs, which might affect local climate and cause milder temperatures. The results might also be affected by the reduced data samples for the two said stations.

Arlanda and Tullinge were identified as the coldest locations within the analysed area. There was also a significant difference between them, with Tullinge being the colder station. It was noted that these two stations are located inland, further away from large water bodies than the warmer stations of Adelsö and Skarpö. This might again indicate the coastal effect on temperature averages, because all four of these stations were located far away from the

city centre of Stockholm in rural locations that are not densely populated (Fig. 3).

The temperature means for all investigated weather stations and for all data sources (SMHI used this paper's statistical analysis, and IWEC and OB from online databases) were placed together in Table 3 and sorted by the ascending temperature mean. There was only one IWEC file available for the Greater Stockholm area, and its location was Arlanda. The OB weather files database offered two files for each station. The one which had the addition of '2004-2018' in the name was generated using this exact time period or shorter time span within it, while the other version was generated using an unspecified time span. The IWEC file's average of model years was the oldest.

The comparison table (Table 3) shows that for three out of six investigated locations the SMHI sourced temperature mean for the most recent years 2008-2020 expressed higher temperature mean than the weather files. In case of Skarpö and Bromma, the latest model years resulted in higher temperature means when comparing all three means for each location. The difference is especially pronounced for the temperature means that were modelled using larger time spans dating back to the 1980s, such as Bromma (OB) and Arlanda (OB). Their means were about 0.5 K lower than the two other respective means. It is noteworthy that the lowest temperature mean was obtained from the Arlanda IWEC file data, which is still a commonly used source of weather data for simulations.

Weather station (source)	T mean /°C	Years
Stockholm (OB)	8.19	2002 - 2019
Stockholm (SMHI)	8.12	2008 - 2020
Stockholm 2004-2018 (OB)	7.98	2005 - 2017
Adelsö (OB)	7.78	2002 - 2019
Skarpö (SMHI)	7.76	2008 - 2020
Skarpö 2004-2018 (OB)	7.75	2004 - 2018
Bromma (SMHI)	7.71	2008 - 2020
Bromma 2004-2018 (OB)	7.70	2004 - 2018
Skarpö (OB)	7.66	1999 - 2018
Adelsö (SMHI)	7.59	2008 - 2020
Adelsö 2004-2018 (OB)	7.41	2004 - 2017
Arlanda 2004-2018 (OB)	7.27	2005 - 2018
Arlanda (SMHI)	7.16	2009 - 2020
Bromma (OB)	7.09	1980 - 2011
Tullinge (SMHI)	6.76	2008 - 2020
Arlanda (OB)	6.69	1981 - 2013
Tullinge (OB)	6.66	2002 - 2019
Tullinge 2004-2018 (OB)	6.66	2004 - 2016
Arlanda (IWEC)	6.49	1984 - 1993

Table 3. Weather station temperature data from different sources sorted by ascending temperature mean.

The order of the Table 3 is similar to the post hoc classification from Table 2, with some exemptions which were discussed above. The overall difference between the lowest (Arlanda OB) and the highest (Stockholm OB) temperature mean from Table 3 is 1.7 K, which for an annual average difference of a relatively small geographical area is substantial. Based on simple hand calculations of building heat balance using a degree hours method (Letherman and Al-Azawit, 1986), such a discrepancy in annual average temperature could have a 12 % to 19 % incremental impact on the predicted heating energy use, depending on the indoor temperature setpoint through independently of the rate of heat loss. Miscalculated heat balance and mismatched energy performance predictions

can lead to poor design and planning. This can, for instance, result in excessive and redundant insulation added onto the building envelopes in order to meet energy requirements, which may further cause potential overheating issues in the summertime (Porritt et al., 2012).

2.2. Spatial and temporal differences - Sweden

The temperature estimated means based on measurement data from SMHI and the corresponding TMY temperature averages from IWEC data were contrasted in Table 4 and sorted in a descending order by the emmeans. IWEC's temperature averages were between 0.65 K and 1.3 K lower than the mean based on the recent 11 years of measured data. There were significant differences between the locations, which resulted in 5 distinct statistically different groups (see also Fig. 4). Comparing the years instead, only year 2010 was colder than the IWEC TMY. Comparing relative humidity means in the same manner, the differences between SMHI and IWEC data means were negligible and inconclusive; there were very small differences between the investigated locations.

The temperature means from the recent weather observations were higher for all locations in respect to the IWEC weather files. Table 4 shows the impact of the difference on heating demand predictions; the percentages were calculated using the same simple degree hours method as previously (Letherman and Al-Azawit, 1986). An overestimation between 4 % and 12 % is expected, depending on the location. Colder locations are less affected by the rising annual temperatures, because the difference constitutes a smaller fraction of the temperature differential when considering the same heating setpoint temperature.

Location	Group	emmean (SMHI) /°C	IWEC average /°C	Difference /K	Heating energy difference
Malmö / Copenhagen	Α	9.40	8.32	1.08	8-12%
Gothenburg	В	7.28	6.53	0.75	5-7%
Stockholm	BC	7.14	6.49	0.65	4-6%
Karlstad	С	6.75	5.92	0.83	5-7%
Östersund	D	3.86	3.15	0.71	4-5%
Kiruna	Е	0.21	-1.09	1.30	6-7%

Table 4. Annual temperature means for SMHI observations for years 2010-2020 and IWEC weather files.

The comparison of annual maximum and minimum temperatures was presented in Table 5. All recent observations show higher maximum annual temperatures than those of the IWEC files, which may introduce overheating issues in buildings. The temperature minima, on the other hand, were both higher and lower depending on the location. Thus, no clear trend was observed, and the impact that the changes in temperature minimum might have on the heating peak load is smaller than of the heating energy difference - up to 7 % only.

Table 5. Annual temperature extremes for SMHI observations for years 2010-2020 and IWEC weather files.

Location	T _{max} emmean /°C	IWEC T _{max} /°C	Difference /K	T _{min} emmean /°C	IWEC T _{min} /°C	Difference /K	Heating power difference
Gothenburg	28.3	27.1	1.2	-14.1	-15.9	1.8	- 7 %
Karlstad	28.3	26.3	2	-18.3	-19.5	1.2	5 %
Kiruna	25.4	22.7	2.7	-31.6	-29.2	-2.4	- 4 %
Malmö / Cph.	29.6	26.8	2.8	-11.5	-9.6	-1.9	3 %
Östersund	26.7	26.5	0.2	-23.5	-25.7	2.2	5 %
Stockholm	29.1	27.1	2	-18.3	-17	-1.3	- 5 %

Radiation data from SMHI calculated emmeans and IWEC weather files was compared in Table 6. The recent SMHI measurements recorded higher averages than the older TMY model years with up to 10 % increase. This does not yet indicate a trend, but it is worth noting that for all locations there was an increase in the global radiation average. This phenomenon could be related to the potential discrepancy between the estimate-based radiation data, typically used in the weather file generation, and ground-based measurements. IWEC files are based on estimates from cloud coverage and other weather parameters (ASHRAE, 2001), while OneBuilding radiation estimates use satellite-based

models (OneBuilding Climate, 2021). Satellite-based data allows to generate sky models and calculate surface irradiance at virtually any location, which increases data accessibility and improves applications promoting solar energy implementation (Huld et al., 2012), but the models can suffer accuracy loss (Psiloglou et al., 2020).

Similar comparison could not have been performed for the sunlight duration data, because SMHI and the TMY data had different ways of accounting for the direct sunlight duration.

Location	Group	emmean (SMHI) /Wm ⁻²	IWEC average /Wm ⁻²	Difference / Wm ⁻²	Change
Malmö / Copenhagen	А	233	219.8	13.2	6.0 %
Karlstad	AB	227	221.4	5.6	2.5 %
Stockholm	В	226	204.7	21.3	10.4 %
Gothenburg	В	223	219.9	3.1	1.4 %
Östersund	С	201	196.4	4.6	2.3 %
Kiruna	D	177	163.7	13.3	8.1 %

Table 6. Annual global radiation means for SMHI observations for years 2010-2020 and IWEC weather files.



Figure 4. Annual global radiation average over measurement years and the IWEC year.

The graph presenting global solar radiation means from the last eleven years data in Figure 4 does not suggest that there are trends or changes in the means over time. What can be seen, however, is that the weather file IWEC radiation mean is generally quite low in comparison to the annual measurements. This increase may potentially have an effect on solar potential, energy, and daylight simulations; however, a previous study on weather data for daylight simulations showed that the impact is quite insignificant (Iversen et al., 2013).

All the individual post hoc comparisons of the Swedish weather locations were combined in one chart in Figure 5. This method of presentation is proposed for the purpose of comparing multi-parameter post-hoc comparisons. The graph can be read in multiple ways. First, it can be noticed that the order of locations by temperature as well as by solar parameters, particularly by radiation, roughly follows the latitude order from southernmost (Malmö) to northernmost (Kiruna) location. Special attention might be paid then to those locations which deviate from the latitude order in those parameters. One can also read the graph by looking at a certain location in respect to others. Gothenburg, for instance, is warm, but not exceptionally warm for its latitude as it does not deviate in respect to the latitudinal order. It is also rather humid and often cloudy since the radiation and sun duration are below latitudinal expectations for Gothenburg's latitude. It can be also assessed from the graph that Stockholm, Karlstad, and Gothenburg share similar climates. We think that this method for comparing climates proved easy to interpret and hence was chosen over the PCA biplots presentation method.



Figure 5. Combined post-hoc comparisons (data included IWEC yearly averages) and latitudes.

4. Conclusions

This paper analysed difference in weather files based on location of the weather stations and observations reference period on the example of the Swedish capital city agglomeration and Sweden as a country. The scope was to understand how the selection of weather files might affect BPS. The analysis showed the importance of keeping weather data for BPS updated, as it was seen that inadequate time and location that a weather file was generated from may have significant consequences on BPS.

The study brought to the attention of BPS analysts that there might be a substantial deviation in urban temperature from the respective rural-based weather data. Choosing an incorrect weather file for BPS can have a significant impact on simulation accuracy. BPS practitioners should be aware of the type of the location (rural/urban) that the selected weather file is from. In case of a mismatch in building site and weather station location type (e.g., a urban development and a rural weather file), adjustments may be advised to reduce the discrepancy. To transform a rural EPW file into a more accurately morphed urban file, one can use the Urban Weather Generator (UWG) (Nakano et al., 2015). Future studies should investigate the precision of the UWG transformations in relation to the actual rural-urban differences observed in real life.

There was a clear indication of potential impact from the temperature differences in different weather data sets and the implications they may have on heating and cooling. Climate change and urban heat islands contribute to higher average outdoor temperatures than those recorded in some weather files, which may lead to misestimation of the energy balance. For the heating demand of buildings in Sweden, poor selection of weather files may lead to an overestimation of up to 19 %. While there is a strong tendency for the yearly maximum to increase carrying potential consequences on cooling in buildings, the yearly minimum temperatures saw neither increasing nor decreasing trends, and thus, the impact on dimensioning of building heating systems is inconclusive.

Regarding solar weather parameters, it is uncertain whether the observed increase in average global radiation can be perceived as a trend. Previous research suggests that the impact on daylighting BPS is thus far limited and possibly negligible. Solar weather observations and the potential temporal differences due to climate change should be continuously inspected, and the consequences on BPS should be further investigated. Future work should examine the impact of the weather data differences on solar, thermal, and daylighting building performance using full-scale BPS.

5. Acknowledgements

The authors would like to thank the Swedish Energy Agency for funding this research.

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Tailored Architectural Design Method for Coloured Façade Integrated Photovoltaics: An Example from the Nordic Built Environment

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Abstract

Façade integrated photovoltaics (FIPV) is a strategy to deploy solar energy systems in buildings and built environments, especially for high-rise buildings having large façade areas. However, many of the new FIPV are not well accepted by people cause their traditional black or dark blue colour; there is growing interest to develop architectural design methods involving coloured FIPV, where both aesthetical and energy aspects are included. This is exactly the aim of this study, three high-rise apartment towers in Trondheim (Norway) served as case studies. The methodology consisted of three steps. In the first step, the façade colour strategies were developed referring to the colour design guidance of Trondheim and the analysis of the local colour context was performed. Then, the solar potential of building envelope was analysed in ClimateStudio, façade areas were categorized according to solar harvest potential. Finally, façade designs were proposed for the towers and preliminary rough energy generation was also performed. The outcomes indicated that 26% annual household energy consumption can be covered by electricity produced from coloured FIPV.

Keywords: Coloured Façade Integrated Photovoltaics, solar potential, high-rise buildings, Nordic built environment.

1. Introduction

Buildings are the largest energy consumption sector accounting for one-third of the global energy usage and greenhouse gas (GHG) emission (International Energy Agency, 2013). This is also the case of Norway where the building sector consumes for nearly 80% electricity usage (Hestnes and Eik-Nes, 2017). Façade integrated photovoltaics (FIPV) is a strategy to harvest solar energy on-site leading to the reduction of GHG emission. Most of the previous studies are focusing on technical aspects like energy productivity (Saretta, Caputo and Frontini, 2019; Xiang and Matusiak, 2019). However, many of the new FIPV are not appreciated by people cause of the traditional black or dark blue with low lightness PV panels exposed on facades. Architectural integration of new solar technology in the existing urban context is an important issue that should be addressed by architects and urban designers (Farkas *et al.*, 2013). Holistic strategies are needed to promote the application of coloured FIPV (cFIPV) and their integration at both, building and districts scale. This study aimed to propose a holistic design method for the integration of cFIPV on the high-rise buildings in Nordic built environments. A residential community located in Trondheim (lat. 63.4 N; long. 10.4 E - Norway) has been selected as façade renovation case study.

2. Research Aims, Methods and Materials

2.1. Research aims

This study assessed and promoted the cFIPV system in the Nordic built environments from architectural design and technological integration perspectives. The Trondheim city's urban context was investigated for architectural design and its local climate data was employed for solar radiance simulations. With a three-step research process, this study aimed to develop a holistic architectural design method considering both aesthetic, technological integration and estimation of energy productivity aspects when deploying cFIPV for high-rise building typology. The developed method can be adopted as design reference for architects, urban designer for both new and renovation projects.

The research aims of this study are the following:

- 1) Assess and boost the deployment of solar energy systems in the Nordic built environments.
- 2) Propose holistic architectural designs to integrate cFIPV in high-rise buildings in urban context.
- 3) Estimate the preliminary energy productivity of proposed renovation design with cFIPVs.
- 2.2. Research Materials and Methods
- 2.2.1 Case Study Area

The case study area is a residential community located in the city of Trondheim (Sør Trondelag, Norway, latitude 63°250N and longitude 10°270E). Trondheim's urban functions started at the beginning of the 11th century (Petersén, Sandvik and Sveistrup, 2015), and nowadays, it is the third largest city in Norway accommodating around 200 000 citizens (Visit Trondheim AS, 2021). There are many traditional and historical buildings with unique coloured volumes in the city center that present an iconic colourful city image of Trondheim. To preserve the valuable identity and sense of place for long term aesthetic sustainability, for construction projects, there is a demand to respect the tradition of chromatic variation of building facades in Trondheim and employ proper colour design strategies according to different urban contexts. The selected residential community is in the transition area where colourful 'traditional city center' and 'less chromatic suburb area' are overlapping (Figure 1.a) and the community consists of three high-rise buildings (Figure 1.b: Building A is Bynesveien 4A, Building B is Bynesveien 4B and building C is Skjæringen 6) build from 1950s. The three high-rise buildings A, B and C have identical floor plan, façade geometry and height, the surrounding context is a mixture of park with landscape (Ilaparken), traditional wooden houses, modern multi-story buildings and industrial factories near the harbor.



Figure 1. a) on the left: Context analysis of the community surrounding and b) on the right: aerial view of high-rise residential community

For solar radiation climate, Trondheim has sufficient solar irradiance, a typical isolines for mean annual global irradiance of around 99 W/m² (equal to 867 kWh/m²year) on horizontal plane can be expected in this region (Olseth and Skartveit, 1986; European Commission, 2019). To better exploit the solar energy potential in Nordic climate and optimize solar systems integration in building envelopes towards the Zero Emission Neighbourhood, preliminary urban planning analysis at the early design stages are highly recommended (Lobaccaro, Chatzichristos and Leon, 2016). Furthermore, the dominating low solar elevation angle during the year is another important feature to guarantee daylight in Trondheim. Due to the geological location of high latitude ($63^{\circ}250N$), the highest position of the sun in Trondheim is 50,00°, which happens between the 19th and the 22nd of June. While, in more than one-third of the daytime throughout the year, the solar angle is between 0° to 10° (Matusiak and Anter, 2012). This daylight feature indicates the importance of investigating the façade integration of PVs besides employing roof areas in Trondheim.

2.2.2. Research method

The research method in this study consisted of three steps. The first two steps of the proposed method included systematic investigations of urban context (first step) and façades (second step) to identify limitations and possibilities in relation to the overall architectural design, while the third step contained a series of solar potential simulation, concrete cFIPV design proposal for the case studies of high-rise buildings and the related calculation of energy production from cFIPV.



Figure 2. Illustration of Three-step research method

In the first step, the analysis focus was on the criticity from architectural perspective. The "Criticity" matrix developed by Munari Probst and Roecker (Munari Probst and Roecker, 2015) has been employed. The "Criticity" matric includes both urban sensitivity and façade's visibility (Figure 3-4): for a planned solar system in a given urban context, its criticity level will be influenced by both the system visibility and the context sensitivity. Higher sensibility (e.g. traditional urban center) and higher system visibility (i.e. façades or roofs easy to be observed from close or remote distance) will lead to higher criticity level requiring well-integrated solar system solutions, and vice versa. The theory could provide guidance for BIPV application in urban context.



Figure 3. "Criticity" matrix according to Munari Probst and Roecker (Munari Probst and Roecker, 2015)



In the second step, colour design strategies for the façades of high-rise buildings in the case study area was investigated based on colour harmony concepts, the colour design rules of the city of Trondheim (Booker and Angelo, 2018), as well as the relationship between solar cell's colours and energy production.

The concept of colour harmony has been widely accepted and discussed for centuries, contemporarily, colour research with observer-participated experiments demonstrated that colour pairs with similarity in hue or chroma, difference in lightness are evaluated more harmonious (Hård and Sivik, 2001; Schloss and Palmer, 2011). A modern Natural Colour System (NCS) colour system, which is also the national standard in Sweden and Norway, suggests that compositions of colours with similarity in one or more of the colour attributes (e.g. hue, chromaticness) are tend to be more appreciated (NCS, 2019). In this study, the NCS colour system and colour harmony concepts were employed, façade colour designs would employ colour combinations in same or similar hues but with difference in lightness. Besides, to respect and preserve the local colour identity and urban images, Trondheim's local colour characteristics were considered as design reference. Colour is one of the key aspects of the image of the city (Lynch, 1960). For architects and urban planners, it is essential to consider the characteristics of the place to prevent prejudicial operations when making colour selection for designs (Zennaro, 2017). To guarantee a high architectural quality for cFIPV design in urban context, colour design strategies like colour plan or colour palette based on local urban context have been tested in many cities and they are practical tools to generate façade colour design fitting the surrounding while strengthen the local identity simultaneously(Brino, 2009; Sibillano, 2011). Angelo and Booker registered the nominal colours of around 200 buildings in the city of Trondheim using the NCS index and NCS colour

scanners. The general colour design rules (Figure 5) for Trondheim (Angelo and Booker, 2016) was proposed: 1) typical hues in Trondheim are in the range from reddish hues to greenish hues, bluish hues are very rare and violet ones are not existing; 2) minimum chromaticness should be 1%; 3) maximum chromaticness is 50%; 4) Blackness should be in the range between 3-5% to 70%.





Figure 5. Trondheim's colour design general rules in NCS diagrams, adapted from Angelo and Booker (From left to right: 1. Typical hue range; 2. Chromaticness range; 3. Blackness range. (Angelo and Booker, 2016)

Figure 6. The overall colour palette of Trondheim according to Angelo and Booker (2018)

An overall colour palette (Figure 6) of Trondheim was also generated by Angelo and Booker (2018), presenting most typical existing colours of different building typologies, e.g. small wooden building and large rendered/brick building. For the energy production aspect, Røyset et al. (2020) found that, the lightness of the colour was the most important parameter affecting the electricity production of coloured photovoltaics, lower lightness level led to higher energy efficiency. With a medium lightness $L^* = 50$, opaque coloured solar cell modules based on crystalline silicon cells can reach 84%-97% performance of traditional black photovoltaics. In addition, photovoltaic with green hue was more efficient than photovoltaics in other hues with the same lightness level. The diagram of relative loss (P) versus lightness (L*) (Figure 7) developed by Røyset et al. was employed in this study as a practical tool for architects to quickly estimate the coloured PV efficiency range.



Figure 7. Relative loss (P) versus lightness (L*), according to Røyset et al. (2020)

Based on colour harmony concepts and the colour design rules of the city of Trondheim as well as the relationship between colour (hue and lightness) and energy production, a detailed colour palette for the three high-rise buildings was generated accordingly, serving as practical tools for architectural design with cFIPV in urban transition areas of Trondheim.

In the last step of the methodology, a series of solar potential investigations for FIPV were conducted for the façades of the three high-rise buildings through solar radiance mapping in ClimateStudio (Solemma, 2021). Built on EnergyPlus and a novel RADIANCE-based path tracing technology, ClimateStudio is an advanced plugin for Rhinoceros and can serve as a fast and advanced environmental performance analysis tool for the architecture, Engineering and Construction (AEC) sector. To obtain an overview of solar potential of different facades, a first-round solar irradiance analysis (with sensor spacing of four meters) on annual basis was conducted through ClimateStudio by simulating the 3D model that reproduces the residential community objected of this study and its neighbourhood area. The weather data climate (.epw) of Trondheim has been used. Both direct and diffuse solar irradiation, as well as solar mutual reflections from the surrounding environments (ground, facades, ground) were simulated, the 'rtrace' parameters used for Radiance-based simulation were shown in Table 1, while the materials set for buildings and landscape were displayed in Table 2, the facades reflectance of high-rise apartment buildings were set with reference of current commercialized Photovoltaics, e.g. KromatixTM colored solar panels (SwissINSO, 2018; Kameleon Solar, 2021)

Table 1 - Set of "rtrace" parameters used for the Radiance-based simulations

ambient bounces	ambient division	ambient super samples	ambient resolution	ambient accuracy	specular threshol	direct d sampling	direct relays	
1 – 3	1000	20	300	0.1	0.15	0.20	2	
	Table 2. Materials setting for solar radiation mapping in ClimateStudio							
3D Model co	mponents	Materials	Туре	Surface	Roughness	Rvis (tot)	Rvis(diff)	
High-rise fac	ades	Exterior wood wall	Glossy	Exterior building	0.2	14.7%	14.2%	
Neighbourho	od buildings	Bright Concrete wall	Glossy	Exterior building	0.3	36.9%	36.8%	
Landscape gr	round	Grass 5	Glossy	plant	0.2	15.7%	15.6%	

The simulated annual solar radiation values were in the range of 0-1100 kWh/m²year. To specify the solar potentials of different facades and to select the most suitable facades for cFIPV deployment, 5 ranges of values were set: *Very high* (880-1100 kWh/m²year), *High* (660-880 kWh/m²year), *Medium* (440-660 kWh/m²year), *Low* (220-440 kWh/m²year), *Very low* (0-220 kWh/m²year) (Lobaccaro *et al.*, 2019).

Based on the findings of the first two steps and the first-round solar energy potential data, a design proposal with integrated coloured photovoltaics for the architectural façade renovation has been developed for the three apartment towers. Finally, annual electricity generation of the proposed cFIPV façades was conducted. To specify the effective areas that would be applied with cFIPV for each façade, detailed solar radiation mapping with sensor spacing of two meters was conducted. The threshold of 440 kWh/m²year for effective area and the reduction factor R calculation used in Lobaccaro et al. (2019) was employed as reference. In this study, the Reduction factor R caused by self-shading is defined as:

$$R = \frac{\text{Aera with irradiation value>440 kWh/m2year}}{\text{Gross façade area (exclude windows)}}$$
(eq. 1)

Detailed R values were obtained through calculation according to the solar radiation simulation of each façade. Thus, the energy calculation was conducted with the following equation 2:

Energy Production= $\sum_{i=1}^{n} (A_i * ASI_i) * EAE*PR$ (eq. 2)

Where A is the effective façade area, ASI is the average solar irradiation on effective area of each façade, EAE is the estimated average efficiency of cFIPV, PR is the performance ratio (80%). Some assumptions were made for the energy calculation: the efficiency of traditional black PV as a reference was set to 22%.

3. Result

3.1. First step: Urban context and façades analysis

The community's neighbourhood has both, traditional wooden houses in vivid colours (Figure 8 a), which are characteristic for Trondheim in Mellomila and Ilsvikøra areas, and contemporary multi-story buildings characterized by less saturated colours. Also, a bit further north, there are factories in grey colours (Figure 8 b) near the waterfront.



Figure 8. a)/on the left: Traditional colour wooden houses in neighbourhood; b)/ on the right: Industry buildings in grey colours

According to the "Criticity" matrix (Munari Probst and Roecker, 2015), architectural integration of photovoltaics in urban context needs to consider the urban sensitivity of local context and the visibility of facades. The case project

has high system visibility since the towers are the tallest buildings in the area and their vertical facades are visible from close and remote distance (Figure 9) as well as from most of the places in Bymarka (hill surrounding Trondheim) and the harbor. The surrounding can be categorized as medium sensitive context (Figure 3). Therefore, the case project has *high-medium* criticity level and it requires high architectural integration quality for BIPV systems.



Figure 9. High system visibility of the towers from close (left, nearby Ilaparken) and long distance (right, Ilsvikøra near the harbor)

3.2. Second step: Façade colour design strategies at neighbourhood scale

Thanks to the rapid development of coloured PV technology, architects can now have high freedom in choosing coloured PV products or even order PVs in customized colours (Eder *et al.*, 2019). Among various coloured PV techniques, the products based on interference colour effects are most promising. Bläsi et al. (2021) from Fraunhofer ISE have developed a series of novel MorphoColor PV sample modules with high efficiency (more than 90% of a traditional black PV), colour stability, and compatibility with industrial production. The Morphocolor technique applies a thin-film stack on the top of a monocrystalline silicon solar cell and generates rich colour choices through the Bragg reflection effect (a type of interference). A commercialized brand with similar interference principles, the KromatixTM PV from SwissINSO SA, have already been integrated successfully in several real projects, showing the application feasibility (Jolissaint *et al.*, 2017). In economic aspect, according to Kutter et al.(2018), the manufacturing cost of MorphoColor PV modules is 93-160 ϵ/m^2 , demonstrating attractive economic competitiveness when compared with the cost of traditional non-electricity-generating cladding materials like brick (60-100 ϵ/m^2) and wood (50-180 ϵ/m^2). Therefore, the authors believe that the coloured PVs employing interference colour principles could be ideal candidates for this renovation project.

Based on colour harmony concepts and the colour design guidance of the city of Trondheim developed by Angelo and Booker, a series of NCS hues including Y80R, Y70R, Y30R, Y20R, G30Y (Figure 10 a) were selected for cFIPV design. These hues are within the typical hue range of Trondheim, common in medium or less sensitive context (e.g., in stone façades or large rendered façades) outside Trondheim's traditional center and was selected in respect to current yellowish and reddish façade colours of the three high-rise buildings. For the selected hues, colour harmony strategy of constant chromaticness but various blackness was employed to create a detailed NCS colour palette (Figure 10 b) for cFIPV of the three high-rise apartments: Y80R, Y70R with 30% chromaticness, Y30 R, Y20R with 40% chromaticness and G30Y with 20% chromaticness (Table 3), while the most common yellowish and reddish NCS colours in current Trondheim contexts varies between 30% or 40% chromaticness, and typical greenish NCS colours have around 10% chromaticness. Architects or urban designers could use cFIPV products with colours from this colour palette or request PV manufactures to produce customized cFIPV of certain desired colour from this palette for this case study (Figure 11).

Table 3. Col	our palette	for cFIPV	of the case	study
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Hues	NCS colours (with blackness in between 70% to 20%)	Chromaticness
Y20R	S6030-Y20R, S5030-Y20R, S4030-Y20R, S3030-Y20R, S2030-Y20R	30%
Y30R	S6030-Y30R, S5030-Y30R, S4030-Y30R, S3030-Y30R, S2030-Y30R	
Y70R	S5040-Y70R, S4040-Y70R, S3040-Y70R, S2040-Y70R	40%
Y80R	S5040-Y80R, S4040-Y80R, S3040-Y80R, S2040-Y80R	
G30Y	S7020-G30Y, S6020-G30Y, S5020-G30Y, S4020-G30Y, S3020-G30Y, S2020-G30Y	, 20%



Figure 10. a)/on the left: selected NCS hues for cFIPV design; b)/ on the right: detailed NCS colour palette for cFIPV design



Figure 11. Potential application of generated colour palette for high-rise tower facades

3.3 Third step: Façade solar potential analysis and cFIPV design

3.3.1. Façade solar potential analysis

From the first-round solar potential analysis in ClimateStudio (Figure 12), an overview of solar potential of different facades for FIPVs application was obtained. Southern facades had the highest solar potential-*Very high*, followed by eastern facades and western facades with *medium* solar potential, while northern facades obtained *low* or *very low* solar potential (Figure 13-14).



Figure. 12 Solar radiation mapping of the high-rise community and its neighbourhood area (with sensor spacing of 4 meters)

Figure. 13 Selected façade areas suitable for cFIPV deployment



Figure 14. Solar potential on different facades

Façade areas with generally *medium* to *very high* solar potential were selected as suitable areas for cFIPV deployment, the areas were marked in different colours in the top aerial view (Figure 13), areas with solar potential lower than 440 kWh/m²year were not included for cFIPV design (Lobaccaro *et al.*, 2019). For each of the selected facades, detailed solar radiation mapping was also conducted, providing more accurate solar potential data (Figure 15-17) for cFIPV design. The simulation showed that, for each façade, the solar irradiation values were not evenly distributed (especially for western facades), this was mainly due to the self-shading or inter-building shading effect. The partial areas with low or very low solar potential were omitted for cFIPV design through applying reduction factor R.







Figure 16. Detailed solar radiation mapping of Building B (Southern, Eastern and Western facades)



Figure 17. Detailed solar radiation mapping of Building C (Southern, Eastern and Western facades)

After the reduction, only effective façade areas are left for cFIPV application. The average solar irradiation (ASI) of each simulation sensor's region is illustrated at the sensor's position on façades (i.e., the small numbers in Figure 15-17). Through area weighted averaging, the average solar irradiation of each façade can also be obtained (Table 4).

3.3.2. cFIPV design and energy productivity estimation

The colours for cFIPV panels were chosen from the detailed NCS colour palette (Figure 9 b), with NCS colours in same or similar hues, same chromaticness but different lightness, a pixelization design proposal (Figure 18) combing cFIPV panels in different lightness levels on facades was generated. A smooth colour transiting effects could be achieved through the pixelization at module level, which leaded to a medium lightness level (L* around 50) for the overall facades, considering both aesthetic performance and demands of energy productivity (Xiang *et al.*, 2021). The reddish hues of Y80R, Y70R and yellowish hues of Y30R, Y20R were selected for the main facades, showing a respect to existing colour identity and support the high contextual integration quality from architectural aspect. cFIPV panels in green colours were selected to equip small areas with very high or high solar potential, e.g., balcony areas. Façade areas not suitable for cFIPV were also designed with coloured non-PV claddings, providing a continuous aesthetic overview.



Figure 18. Proposal of cFIPV design for high-rise community

The Reduction factor R values caused by self-shading were obtained through calculation according to the solar radiation simulation of each façade (Figure 15-17) and were described in Table 4.

Table 4. Description of Effective areas for cFIPV

Selected Façade areas (exclude windows) (m ²)	General Solar	Reduction factor R	cFIPV covering	Effective areas	ASI (kWh/m ² year)		
, , , ,	potential		ratio	(m ²)	, , ,		
	Southern Walls	314	Very High	0.9	90%	283	917
-----------	------------------	-----	-----------	------	------	-----	-----
iilding A	Southern balcony	32	High	1	100%	32	818
	Eastern Walls	332	Medium	0.9	90%	299	584
	Eastern balcony	59	Medium	1	100%	59	583
B	Western Walls	335	Medium	0.48	48%	161	460
	Western balcony	66	Medium	0.89	89%	59	503
	Southern Walls	314	Very High	0.8	80%	251	858
8	Southern balcony	32	High	1	100%	32	786
Building	Eastern Walls	332	Medium	0.9	90%	299	540
	Eastern balcony	59	Medium	1	100%	59	524
	Western Walls	335	Medium	0.32	32%	107	503
	Western balcony	66	Medium	0.5	50%	33	496
	Southern Walls	314	Very High	0.85	85%	267	884
(۲	Southern balcony	32	High	0.95	95%	30	784
gui	Eastern Walls	332	Medium	0.9	90%	299	520
ibliı	Eastern balcony	59	Medium	1	100%	59	521
B	Western Walls	335	Medium	0.48	48%	161	476
	Western balcony	66	Medium	0.87	87%	57	531

The efficiencies of cFIPV with colours from the detailed colour palette were listed in Table 5, in range of 13.6% to 21.1% (the efficiency of reference traditional black PV was set to 22%, the performance ratio (PR) was set up to 80%.). The L* levels of chosen NCS colours were in range of 28-75, estimated relative efficiency of cFIPV in different NCS colours was obtained with reference of the relationship diagram between Lightness and Relative loss (Figure 9) according to Røyset et al.(Røyset, Kolås and Jelle, 2020). An average efficiency of 17% was assumed for average lightness of the pixelization of cFIPV panels (the cFIPV façades design has an area weighted average L* around 50).

Table 5. Estimated relative energy efficiency of cFIPV with selected NCS colours

NCS colours of cFIPV	L*	Relative efficiency loss (P) compared with a black PV with 22% efficiency	Estimated relative efficiency	Estimate efficiency
S6030-Y30R	38	10%	90%	19.8%
S2030-Y30R	72	35%	65%	14.3%
S5040-Y80R	32	8%	92%	20.2%
S2040-Y80R	63	20%	80%	17.6%
S7020-G30Y	28	6%	94%	21.1%
S2020-G30Y	75	38%	62%	13.6%

Finally, an energy generation estimation is also conducted through equation 1, by employing the simulated solar irradiation on the facades, effective areas of facades for cFIPV and the efficiency of colour photovoltaics. Divided by the total heated floor areas (9000 m²), the energy productivity of proposed cFIPV façades is 25 kWh/m²year, which can cover 26% of household energy demand according to current enforced Norwegian building code TEK17 (annual computation of 95 kWh/m²year for the apartment) in all-electric scenario (Voss and Musall, 2013). Compared with the case if the façades were covered by traditional black PVs (the electricity production divided by the total heated floor area is 32 Wh/m²year), the cFIPV façades generate 22% less energy. The result shows that cFIPVs with holistic architectural design can serve as a promising method to harvest solar energy in built environment. However, the ZEN ambition level ZEN-O (The Research Centre for Zero Emission Neighbourhoods and in Smart Cities, 2018) was not achieved in this study showing that there is still potential to improve for reducing energy consumption or utilizing other renewable energy source on-site.

3.4 Limitation of this study

This study presents the following limitations: 1) the energy productivities of coloured PVs were just estimated; the use of the lightness level to estimate the cFIPV efficiencies is a quick method. For more accurate data, more complex

and time-consuming energy calculation model (Røyset, Kolås and Jelle, 2020) is needed, for instance, using a series of flat-top reflectance spectra to simulate the reflectance spectrum of cFIPV. In addition, it would be beneficial if real commercialized coloured PVs were available for data from experimental campaign monitoring. 2) the contribution of the presence of the snow in winter season in terms of solar reflections that would impact the energy production of FIPVs was not considered in this study. Therefore, more advanced simulation methods and calculations supported by experimental data might be needed to investigate this phenomenon further.

4. Conclusions and further developments

The energy simulation results show that with holistic architectural design, façade integrated photovoltaics can serve as a valuable strategy to harvest solar energy in built environment and reduce GHG emission in the studied neighbourhood, while preserving local urban image and architectural identity. This holistic architecture method could be deployed in both, new developments, and renovation projects, in similar Nordic climate.

Further research can also investigate the GHG impact of proposed design solutions with already commercialized coloured photovoltaics products from life-cycle perspective. More practical data is needed from the industry and cFIPV markets. Another aspect that could be further investigated is the energy flexibility study of cFIPV for building facades, due to the uneven distribution of solar energy throughout a year, the production of on-site electricity is also unevenly distributed.

5. Acknowledgement

This work was performed within The Norwegian Research Center for Sustainable Solar Cell Technology (FME SUSOLTECH, project number 257639/E20). The center is co-sponsored by the Research Council of Norway and its research and industry partners.

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N-01. ISREE-14

Interactive Solar Energy Exhibition

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Abstract

Public understanding of science PUS is a central concept among science communicators. In 2011 we introduced the acronym PURE, Public understanding of renewable energy. PURE is proposed as an important sub-concept of PUS. Four reasons for the importance of public understanding of renewable energy are: (i) The earth is a lonely planet in a vast space, (ii) The earth is a planet alive with a dead sister and a dead brother. (iii) Anthropogenic influence on the world's climate. (iv) One major source of greenhouse gases is combustion of fossil fuels, which has to be replaced by increased energy efficiency and renewable sources of energy. There are many channels that can be and are tried to achieve PURE, among them interactive exhibits in science centres. We have over the years built a number of interactive solar energy exhibitions and we suggest that an interactive exhibition could both be part of the newly established digital ISES Solar Energy Museum and a Science Center IRL in Strömstad or elsewhere.

Keywords: public understanding of science, public understanding of renewable energy, ISES Solar Energy Museum

1. Introduction: Public Understanding of Science

Public Understanding of Science (PUS) is today an established concept. There is even since 1992 a scientific journal with this name. A 3-fold definition of PUS given by Baur is

(i) "Debunking of superstitions, half-knowledge, complete and utter ignorance, misunderstanding and mumbojumbo, and virulent memes that give rise to anti-science."

(ii) PUS is to "improve science literacy, to mobilize favorable attitudes in support of science and new technology, to increase interest in science among young people and other segments of society, and to intensify public's engagement with science in general and for the greater good of society."

(iii) "PUS considers common sense as an asset" and PUS research should "chart out the public controversies arising from new developments and in different regions of the world" exemplified by "the impact of the climate of opinion on knowledge production." (Baur 2009)

Today, in the early 2020ies, with so much fake news abundant, PUS seems even more important than a dozen years ago.

During the planning of Sweden's first science center The Futures' Museum, one of the authors (Broman) gave following seven reasons for creating a science center:

(i) Give an insight that science is understandable.

- (ii) Awaken curiosity.
- (iii) Give people the courage to experiment.
- (iv) Facilitate public understanding of science.
- (v) Provide preparedness to withstand superstition and pseudoscience.
- (vi) Amuse and entertain.
- (vii) Provide aesthetic experiences. (Broman 1984, 2004, 2005).

Underlying the statements is the notion that PUS is important, which scientists happily believe, and we of course agree, but it is not as simple as that. There are e.g. so many different sciences (which in turn are divided into many disciplines). A rather popular notion is that "science" is that same as "natural sciences", but that is not the

case. Science also "includes engineering and medicine, the social sciences and humanities, old and new disciplines with clear boundaries, but also ... fuzzy transdisciplinary techno-sciences" (Baur 2009).

It is also vital to identify target groups, since some may be more important than other. Loosely defined target groups frequently mentioned are young people (in the world of science centres often restricted to the "7-eleven group" of elementary school children), voting adults, and decision makers. Other interesting group may include teenagers, refugees, religious fundamentalists, senior citizens, people living in villages as well as cities, just to name a few.

It is also important to identify groups of science communicators. As an example, The European Science Communication Network ESCOnet, 2005-8 developed and conducted a series of workshops on science communication training aimed at young post-doc researchers (Miller et.al. 2009).

2. Public Understanding of Renewable Energy

PUS is important for a variety of target groups including common public. A presently important subset of PUS is Public Understanding of Renewable Energy. In 2011 we introduced the acronym PURE (Broman, Kandpal 2011, 2013): Public understanding of science PUS is a central concept among science communicators. Public understanding of renewable energy PURE was proposed as an important sub-concept of PUS. Four separate important questions for a PURE research project can be identified: (A) Is PURE important? (B) Which issues of PURE are the most important ones, according to renewable energy scientists? (C) What understanding of renewable energy has the general public today, worldwide? (D) How to achieve PURE?

There are many channels that can be and are tried to achieve PURE: Newspapers, TV programs, social media, books, interactive exhibits in science centres, lessons in the school. Different media attract different target groups. Loosely defined target groups frequently mentioned are young people (in the world of science centres often restricted to the "7-eleven group" of elementary school children), voting adults, and decision makers. Other interesting groups may include teenagers, refugees, religious fundamentalists, senior citizens, people living in villages as well as cities, just to name a few.

2.1. Importance of Public Understanding of Renewable Energy (PURE)

Four reasons for the importance of public understanding of renewable energy are:

(i) The earth is a lonely planet in a vast space, not as crowded as the impression one gets from science fiction movies. For humans to move from a destroyed earth to another hospitable planet is just impossible. Present ideas to inhabit planet Mars seems to us utterly unrealistic,

(ii) The earth is a planet alive with a dead sister and a dead brother. Venus is too hot for life due (also) to too much greenhouse gases, while Mars is too cold due (also) to too little greenhouse gases.

(iii) Anthropogenic influence on the world's climate, in particular climate warming due to release of greenhouse gases like carbon dioxide (CO_2) and methane (CH_4) is generally agreed upon among scientists, especially within IPCC.

(iv) One major source of greenhouse gases is combustion of fossil fuels, which has to be replaced by increased energy efficiency and large-scale worldwide dissemination of appropriate technologies for harnessing renewable sources of energy.

A reasonable conclusion is that public understanding of renewable energy is important. An important task of an initiative on PURE would be to identify pros and cons in this respect. There are also several attendant questions: What do professionals - researchers, planetarians, teachers - say? How interested is the public - and different

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target groups - in renewable energy, and what do they already know? Which disciplines in renewable energy science are more important than others? A very crucial role exists of common people in the success of this objective of large scale harnessing of renewable sources of energy, since as adoption as well as design, developing, manufacturing etc, would require their participation.

2.2 Approaches and Means to Achieve PURE

There are of course several different channels that can be and are used in conveying attitudes towards and knowledge of renewable energy subjects listed above. Different media certainly attract different target groups. One of the important tasks is to assess the potential role that science centers with interactive exhibits can play in enhancing PURE. It is worth mentioning that all science centers are not identical – there is a great difference between large science centers (like Nehru Science Centre in Mumbay, Cité de Science and Technologie in Paris or Exploratorium in San Francisco) and smaller ones (like Ekohuset in Strömstad and Molekylverkstan in Stenungsund; both Sweden and the medium-sized Regional Science Center in Dehradun, Uttarakhand, India,).

It is well established that a combination of watching a planetarium show and doing experiments related to the show is very useful (Pettersen 1995, cited in Broman, Kandpal 2013). Traditionally, planetariums used to be devoted basically to astronomy using a classical opto-mechanical star projector. However, today planetariums increasingly concentrate on edutainment shows with astronomic content, using all-dome video technique. Shows related to climate change and its solutions would be easily produced using modern planetarium projectors and would fit nicely under the planetarium dome. Two further opinions on interactivity are listed below:

Michael Spock, former Director of *Boston Children's Museum*, borrowed the Chinese philosopher Confucius' proverb as a motto for the museum: I hear and I forget, I see and I remember, I do and I understand (cited in Ott 2001).

William Glasser wrote: We learn 10% of what we read, 20% of what we hear, 30% of what we see, 50% of what we both see and hear, 70% of what is discussed with others, 80% of what we experience, and 95% of what we teach (Glasser 1990).

An important component of achieving PURE is likely to be interactivity and hands-on experience, and useful environments for this are science centers. Some examples of this are shown below in photographs from the Teknoland outdoor science center 2000-2001: Yourself a sundial, Toddlers' Teknoland, Solar energy surfaces, The greenhouse, The solar heated chess board, Solar energy popcorn, and Solar energy calculators.

3. Educating the General Public

Ordinary people are the ultimate users of energy from the sun and accordingly need basic knowledge and understanding to make use of this new technology and be motivated to use it. A number of ways to educate large populations are readily available. Some proven examples include:

Mass media. This includes newspapers, weekly magazines, radio, and TV. You address professional journalists, and if you manage to teach them some basic facts, they will frequently make a good job in popularizing what they have learned.

Exhibitions. We have built both Science Centre exhibitions (1986 and 1990 on solar energy for the Futures' Museum in Borlänge, Sweden) and travelling exhibitions (Alternative Energy 1976, Solar Energy Exhibition 1989). Also Falun Science Centre (1992-2001) and the outdoor Science Centre Teknoland (2000-2001 in Falun, Sweden) included renewable energy exhibits. The educational value of an exhibition is greatly improved if it provides hands-on experiences. To complement the recent ISES virtual Solar Energy Museum with hands-on exhibits in several places – maybe one of them in Strömstad, Sweden – is hereby proposed.

Trade fairs. Another kind of exhibition is the trade fair with commercial and institutional exhibitors. Such fairs can range in size from the one hundred square meters or so of exhibitions that accompany SERC's Solar Energy Days and exhibitions by Solar World Congresses to the multi-acre exhibition of the UN Conference on New and Renewable Energy Sources of Energy in Nairobi 1981. Such fairs contain up-to-date technological information for many categories of visitors and should be made available both to professionals and to the general public.

Popular lectures, etc. General admission popular lectures sometimes attract good-size crowds, especially if arranged as debates or panel discussions, or if a well-known speaker is featured. Lectures can also be video-taped as webinars, and can, with appropriate solar powered equipment, be shown just about anywhere.

Community college courses. These are excellent in giving interested individuals more-than-basic knowledge. The aim of such courses can even be that every participant builds his own solar collector or any other device.

Social media have recent years grown to be common channels for spreading information and have to be used for reaching especially younger audiences.

Other examples of contributing towards PURE include renewable energy education and training in a 2015 Egyptian village with a program consisting of public presentations, group discussions, simple solar kits, children competitions, technical training workshops, exhibits with working models, working systems, video-training systems, a community library, and organization of regional training workshops with the objective of familiarizing women in developing countries with renewable energy development and technology (Arafa 2017).

Another approach of community college type of educating people that is popular in Sweden is called study circles. A typical study circle consists of a circle leader - the teacher - and 5 to 10 participants. Especially during the nineteen nineties, knowledge about solar heating was spread in many locations in Sweden in this form, where each study group built a solar heating system at one of the participants' house, using a popular build-yourself solar collector kit (Börjesson et.al. 1994). A thorough investigation of this kind of education is presented in a case study (Henning 2000).

4. Interactive Solar Energy Exhibitions

We have over the years built a number of interactive solar energy exhibitions, presented among others at the ISES Solar World Congresses in Denver 1999 and in Göteborg 2003. In the present paper we suggest a modern interactive exhibition that could both be part of the newly established digital ISES Solar Energy Museum as well as a Science Center IRL in Strömstad or elsewhere. Useful experiments that can be included were published in 2016 by us (Kandpal, Broman 2016).

Some of the gadgets developed at Indian Institute of Technology Delhi in early 1980's to offer school level experiments which could be adapted for science center use include:

1. Measuring altitude of the Sun

2. Absorption of solar radiation by different colors - solar heating of water in beakers

3. Absorption of solar radiation by different colors – melting of ice cubes kept in trays coated with different color paints

- 4. Greenhouse effect
- 5. Effect of orientation of the transparent wall on the enclosure air temperature
- 6. Arrangement to measure reflectance of reflecting materials and transmittance of glazings
- 7. Movement of focal line of a linear Fresnel reflector
- 8. Rise in temperature of water in the can at the focus of a conical concentrator
- 9. Composite parabolic trough with a rectangular channel absorber

(Kandpal, Broman 2016)

Examples of Activities Developed and Presented in Teknoland 2000-2001 (the outdoor Science center in Falun Sweden):



Fig.1 A set up to demonstrate greenhouse effect being built at Teknoland. Exhibit label: A higher temperature can be experienced inside the greenhouse (as compared to temperature outdoors) demonstrating the greenhouse effect.



Fig. 2 Yourself a Sun-Dial Exhibit at Teknoland. Exhibit label: Stand straight on a grey stone so your shadow points towards the white stone. What time is it? Since the sun's path over the sky changes a little from day to day, the places of the stones have to be changed from time to time. (Please don't move any stones yourself, let Teknoland's personnel do the adjustments!)



Fig. 3 Solar Heated Chess Board at Teknoland. Exhibit label: Walk around barefoot and feel the difference between black and white squares! Also play. 4 against 1: Two players, white and grey. You play only on white squares. Place the four white pieces along one edge. Place the gray piece at the opposite edge. The players take turns in moving a piece to one adjacent white square. Gray player begins. White is only allowed to move ahead, never back. Gray wins if it manages to pass behind the white pieces. White wins if white shuts up gray so it cannot move. (No piece may jump over another piece.)



Fig.4. Playhouse with PV electricity at Toddlers' Teknoland. Exhibit label: In the house there is a radio, which gets the required electricity from a solar panel on the roof. Cover the solar panel to quiet the radio.



Fig.5. Solar Surfaces Demonstrated at Teknoland. Exhibit label: Feel the different surface temperatures! A black surface absorbs more sunlight than a white or a metallic. A surface turned towards the sun than one that is turned away from the sun. Glazing prevents radiation from the surface. A painted surface radiates heat easier than a metal surface and is therefore cooler.



Fig. 6. Making popcorn using a solar concentrator at Teknoland. Exhibit label: When the sun is visible, rays directly from it can be concentrated into a small area. A reflecting parabolic mirror creates almost a point. A near-parabolic mirror like this one produces a slightly wider spot. The concentrated light gives high temperature, so with a frying pan on that spot it is possible to fry pancakes or pop popcorn. Caution: This exhibit is dangerous and may only be handled by Teknoland's staff!



Fig. 7. Principles of solar collection and solar cooking being investigated by school children.

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Challenges of Education In Energy and Environment: Comparison before and after Pandemic Constraints

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Abstract

Energy systems present a complex and dynamic interrelation between energy, environment, and society. Therefore, properly educating new professionals for the renewable energy sector is a challenging endeavor by itself. The COVID-19 pandemic has imposed an additional challenge on how to engage students in energy and environment education through distance learning. In this paper, we present the methodology applied at the Federal University of São Paulo (UNIFESP) for students of the discipline "Energy and Environment". The graduate student interns developed an integrated methodology of disseminating knowledge about renewable energy and environment for those students and society as a whole. A positive feedback over 95% was obtained from the enrolled students in the period of 2019 - 2020. It was also noticed a failure rate of 24% in 2020 in contrast to zero occurrences in 2019, when face-to-face activities were in place. Finally, we present a brief discussion on the primary challenges and lessons learned during the studied period.

Keywords: Training abilities, Capacity Building, Renewable Energy, Undergraduate and graduate programs, COVID-19 impact

1. Introduction

The Federal University of São Paulo (UNIFESP) is a 25-year-old public university with six campuses in São Paulo state, Southeastern Brazil. This case study was accomplished at the "Institute of Marine Sciences" (IMAR), located in Santos, a medium-size coastal city, 80 km far from São Paulo city. The IMAR is the youngest Academic Institute of UNIFESP, and its primary mission is capacity-building focused on interdisciplinary technological and scientific advances focused on sustainable socioeconomic development of the anthropic activities taking into consideration environmental and human welfare issues. Since 2019, UNIFESP has offered the Interdisciplinary Graduate Program for a Master's degree in Marine Science and Technology (PPG-ICTMAR), where undergraduate students can research renewable energy resource issues in tropical coastal regions and train their teaching competences.

The IMAR/UNIFESP started undergraduate courses in the engineering area in 2012, specifically Bachelor in Marine Science and Technology, Environmental Engineering and Engineering on Petroleum and Renewable Energy Resources. Besides the fundamental energy and science disciplines, both undergraduate courses comprise 360 h in undergraduate disciplines as a pathway to building interdisciplinary knowledge, professional competences, and training abilities to work on renewable energy resources, including solar, wind, hydro, and biomass energy. The discipline "Energy and Environment" is the first discipline of the pathway offered to students engaged in the third year of Engineering courses (UNIFESP, 2012). The primary goal of "Energy and Environment" is to promote the students' first acquaintance with technological, scientific, and social challenges related to the energy transition from fossil fuel technologies to renewable energy resources. The discipline teaching plan includes fundamental concepts on material science, energy policy, energy planning and security, energy meteorology, energy technologies, and environmental impacts from energy generation and consumption. The lecturers expect to introduce and attract young people to professional training to work in a wide range of activities in the energy sector.

© 2021. The Authors. Published by International Solar Energy Society Selection and/or peer review under responsibility of Scientific Committee doi:10.18086/swc.2021.47.02 Available at http://proceedings.ises.org

This work aims to present a brief description of the teaching and learning challenges brought to the discipline classes due to the COVID-19 pandemic crisis. The paper draws a comparison between the learning and train- ing activities developed before (in 2019) and after implementing the health security procedures to deal with contamination risks in 2020.

2. Teaching Methodology

The teaching team comprises a Professor and five masters' students selected to act as teaching interns. The teaching internship is mandatory in Brazilian regulations for the masters' students receiving financial support from CAPES, the Brazilian agency responsible for supporting and regulating the graduate courses. Two of the teaching interns worked in 2019 and the other three worked in 2020. All five had the responsibility of helping the Professor to prepare and execute the teaching plan. The interns' responsibilities included:

- Preparing multimedia and the practical content to be completed in traditional classes (face-to-face) in 2019, and for distance education in synchronous or asynchronous meetings in 2020;
- Conducting debates among students on topics listed in classes planning;
- Supporting students' activities in group dynamics and research assignments;
- Participating in pedagogical meetings with the Professor to plan and discuss the learning activities;
- Preparing and giving one lecture on a specific topic listed in the discipline plan under the Professor's supervision
- Styles for table and figure captions.

In order to enhance information accessibility of topics discussed along with the discipline, teaching interns created the "@ema_brazil" page on Instagram: a digital platform whose objective is to help people to appro- priate the scientific concepts through symbolic images, metaphors representations, practical examples, reading recommendations, art and cultural presentations, and thematic discussions on issues related to energy, environment, and society. The "@ema_brazil" project mission is to share in-depth knowledge about the aforementioned topics in accessible language and provide didactic and technical definitions whenever required. The targeted public is mainly enrolled students, young researchers, technicians, and civil society as a whole.

The evaluation of the teaching-learning process adopted was continuous along with the academic term. It sought to identify the student's progress throughout the semester based on activities that engaged students to look for information and knowledge at reliable and confident sources such as international universities and research institutions. The students had to prepare infographics, digital media projects, thematic games, and debate speeches on specific topics according to the discipline's topics. The "@ema_brazil" Instagram page disseminates the best student media products.

The COVID-19 pandemic crisis required reorganization of the face-to-face activities in the 2019 academic term to the discipline offer in 2020 taking into account the COVID-19 pandemic conditions. The teaching team worked to adapt and create conditions to execute the discipline plan using MOODLE platform to asynchronous interaction, provide reference materials for study, and prepare the discipline activities. Google Meet tools were applied for synchronous meetings and group discussions.

Prior to the beginning of the semester and in order to enhance full engagement in the learning process of all people involved, the Federal University of São Paulo provided training courses on the remote teaching tools available for the teachers. For the socioeconomically vulnerable students, notebooks and cellphone chips for internet access (UNIFESP, 2020) were lent by the fulfillment of a requisition form.

3. Results and Discussions

In 2019, fifty-five students enrolled in the "Energy and Environment" course, and eighty-one students enrolled in 2020. In 2019, all classes happened at the IMAR Building, but the COVID-19 pandemic made it impossible to do so in 2020. In an effort to follow the safety and health protocols, an alternative distance learning methodology was applied. Before the enrollment period, all students were informed about the methodology and the media platform to be used for the virtual meetings along the academic semester of the undergraduate course.

During the academic term in 2020, the students should accomplish several activities, including reading tasks,

watching recommended documentaries and movies, listening to podcasts, preparing texts, and taking part in discussions in synchronous class meetings. All proposed tasks have some correspondence with activities developed in face-to-face classes in 2019.

Since the first virtual meeting of 2020, we already had a great barrier to overcome. Several students did not have access to a reliable Internet connection or electronic equipment (computer or tablet) to support audio and image transmission. Other students did not have an adequate environment to keep full attention on the classes activities. In summary, the synchronous activities did not get the key goal — interact and integrate students group, teacher, and teaching interns. The socioeconomic vulnerability was much beyond the technology access and required to meet alternatives to overcome the lack of time and physical space for students attend classes, even with the university technical support. This issue got worse along the academic semester, and some students had to give up the university activities to help their families deal with home tasks, health issues and financial demands.

Mental and physical well-being are very important for a learning process to succeed. The fear and isolation promoted by a global pandemic severely affected the students behaviour, who showed signs of anxiety and depression, in a way that made all the teaching team more aware of the need to respond the student's emotional worries towards their academical and personal lives as proposed by Morgan (2020). Taking a few minutes of the synchronous encounters to ask the students about how they were dealing with the pandemic impacts on their households and study performance led to changes on the content application of online classes and evaluations, which improved the yet enrolled students' commitment around the end of the semester.

Figure 1 presents the data obtained from the discipline records from the university's academic system and the enrolled students throughout 2019 and 2020's academic terms. It can be noticed a decrease in the number of students that answered the evaluation survey at the end of the semester. The students were asked to provide their vision about the contribution and interaction with Master's students in the discipline activities. For both years, more than 90% of the students declared acknowledgment of the participation of teaching interns and their attributions, with over 95% evaluating interns' performance as "good" or "very good". However, an increase in students' alleged lack of acknowledgment about the activities for the 2020 period was also observed.

Figure 2 presents examples of knowledge dissemination material developed through the methodology. On the left, a publication on "@ema_brazil" Instagram page (Figure 2a), and, on the right, an infographic elaborated by a group of "Energy and Environment" enrolled students (Figure 2b). Such examples highlights the importance of transmitting complex ideas through accessible vocabulary and visually appealing design.

All enrolled students in 2019 had active participation and produced several inspiring products for knowledge dissemination. In addition, high attendance and student engagement during classes with conceptual debates on energy topics were noticed. None of the students failed the course at the end of the semester, but not the same happened in 2020. Distance learning put new obstacles to breakthrough: how to encourage students to engage in debates without feeling the agreement or disapproval of their proposals, and how to maintain students concentrated when they have easy access to several other exciting activities that may distract them from synchronous classes are questions that must be addressed in order to enhance the learning process outcome. In 2020, 24% of the enrolled students failed at the end of academic term.

On the other hand, there's information regarding the development of the teaching interns through the PAD program. Internship certification requires the leading professor to send a personal note and the enrolled students' evaluation to score the interns' tasks and performance to the PAD coordinators at the end of the academic semester. All the interns were approved and certificated on their actions. Given that most of them were pre-viously enrolled in the same graduation course – Marine Science and Technology, it was helpful to work as a junior teacher considering the merge between their old student experience with the new duty of communicating scientific knowledge with the undergraduates already considering, on the content preparation, which terms and subjects would be best or least understandable for the listeners – being that a valuable skill for future works involving not only education, but human resources management in general.

Finally, looking for technical and financial support alternatives and emotional incentives is fundamental to keep students committed to their professional and academic education. There is no doubt that affirmative actions for social inclusion should be planned and executed in Brazilian public universities to avoid increasing student dropout in higher education. The ODS of the Agenda 2030 demands such actions to meet a sustainable socioeconomic advance, reducing social vulnerabilities still impacting Brazilian society.



(a) Student's participation.



Knowledge about the intern's participation





Evaluation of interns

Fig. 1: Comparison of discipline data records in 2019 and 2020.

⁽c) Evaluation of interns.



Fig. 2: Example of science Communication products elaborated by the enrolled students in Energy and Environment discipline: (superior) Post in Instagram network prepared by a student's team discussing solar spectral irradiation reaching the Earth surface (in Portuguese); (inferior) Infographic elaborated by a student's team discussing energy flux in biological ecosystems (in Portuguese)

4. Acknowledgments

Thanks are due to CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for the research fellowships of the authors. Special thanks are due to FAPESP for the financial support for the publication (process number 2021/10132- 8). We also thank the UNIFESP for the infrastructure, technical and pedagogical support for the undergraduate and graduate courses.

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DEVELOPMENT OF OPEN EDUCATIONAL RESOURCES FOR RENEWABLE ENERGY AND THE ENERGY TRANSITION PROCESS

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Abstract

The dissemination of knowledge about renewable energies is understood as a social task with the highest topicality. The transfer of teaching content on renewable energies into digital open educational resources offers the opportunity to significantly accelerate the implementation of the energy transition. Thus, in the here presented project six German universities create open educational resources for the energy transition. These materials are available to the public on the internet under a free license. So far there has been no publicly accessible, editable media that cover entire learning units about renewable energies extensively and in high technical quality. Thus, in this project, the content that remains up-to-date for a longer period is appropriately prepared in terms of media didactics. The materials enable lecturers to provide students with in-depth training about technologies for the energy transition. In a particular way, the created material is also suitable for making the general public knowledgeable about the energy transition with scientifically based material.

Keywords: energy transition, renewable energies, open educational resources, dissemination, digitalization

1. Introduction

The dissemination of knowledge about renewable energies is considered to be a societal task with the highest topicality and urgency. The transfer of teaching content into digital open educational resource (OER) formats is a unique opportunity to significantly accelerate the energy transition at the highest and most efficient level. In addition, multiplier effects can generate additional value for a climate-friendly energy structure change that requires skilled workers. Thus, in this paper the project "OER4EE – technologies for the energy transition" is presented. In this project a consortium consisting of experts in the field of renewable energies from six German universities (Technische Hochschule Köln, RWTH Aachen, Fachhochschule Aachen, Hochschule Bonn-Rhein-Sieg, Ruhr-Universität Bochum and Hochschule Düsseldorf) create open educational resources for the energy transition. The project is funded by the " Ministry of Culture and Science of North Rhine-Westphalia " in cooperation with DH.nrw and lasts from 09/2020 until 08/2022. The produced materials will be available on the internet via the platform ORCA.NRW [1]. The material is published under the license CC-BY-SA 4.0 [2]. This means that the material may be reproduced and distributed further and that it may be changed and built on, including commercially under the following conditions: the author has to be mentioned and it has to be indicated of whether changes have been made. Changes and distribution may only be made under the same license (CC-BY-SA) [2].

In the socially and technologically dynamic field of technologies for the energy transition, today's lecturers use specially created PowerPoint slides. There are no publicly accessible, editable media, that cover the entire learning units in high professional quality, although media didactic approaches would be helpful in many aspects. Some

of the technical content does not change very quickly and a media-didactic presentation would therefore be worthwhile. Another part of the content requires file formats that can be changed quickly in order to keep them up to date.

The project has the task of appropriately preparing the content that remains up-to-date in terms of media didactics, for example with teaching videos, review questions and discussion videos. The materials created in this way also enable lecturers outside the project consortium to provide students with in-depth training.

2. Target group

The main target group as users of the materials created in this project are lecturers and students of engineering. At the six participating universities there are 22 courses for which the material is relevant. These courses are shown in the Figure 1.



Figure 1: Courses at the participating universities in which the material is to be used.

All courses deal with the topic of renewable energies and the system technology required for the energy transition. This includes both bachelor and master degree programs. These courses include the classic disciplines such as electrical engineering and mechanical engineering, but also courses that have been further developed from these disciplines such as "Energy and Environmental Technology", "Environmental and Process Engineering", "Environmental and Resource Management", "Sustainable Engineering" or dedicated to that topic coordinated courses such as "Renewable Energies". Graduates of the planned modules should receive in-depth skills in the assessment and analysis of technologies for the energy transition through digital exercise options. The material is also suitable for making the general public knowledgeable about technologies of the energy transition with

scientifically founded material: It can be assumed that schools with physics courses, energy working groups or the like, as well as interested citizen groups and associations, will use the freely available materials to better inform and educate oneself. In this way, the material also helps to promote innovation and open discussion in society, especially in the conflict-prone area of energy.

3. Content of the teaching/learning offer

The energy transition is a complex topic which, in addition to purely technological perspectives, also has social, economic and environmental perspectives. The project covers many of these aspects, but can only form a nucleus, which is able to lay the foundation for a comprehensive OER offer in the field of "technologies for the energy transition". For this reason, the structure of the OER offer is of great importance. The aim is that the OER offer can also be supplemented after the end of the project and also by actors who are not part of the project consortium. The contents are divided into three groups: technologies for the use of renewable resources, energy storage and efficient energy use. Within these groups, the contents are specified in more detail. In the case of energy storage systems, for example, a subgroup are batteries. These are further classified according to the technology such as lithium batteries. In each subject, the focus is on four different methodological specializations. These are "Technology", "System analysis", "environmental impact" and economics.

Figure 2 shows all subjects in the left column. The participating universities are listed on the first line. The green fields indicate the universities that produce the corresponding content. The yellow fields indicate the universities taking part in the project that use the produced content. In the case of battery storage for example RWTH Aachen and Ruhr-Universität Bochum produce the content and the other participating universities will use this content in their own courses.

		TH Köln	RWTH Aachen	FH Aachen	Ruhr-Univ. Bochum	HS Bonn-Rhein-Sieg	HS Düsseldorf
	Content green: create gelb: take over from others						
5	Renewable energies overview, energy supply of the future						
sies:	Biomass						
ner§ d Sv	Photovoltaics						
le El	Wind energy	L					
wab	Solar thermal	s					
ene	Solar thermal power generation						
ge R	Energy 4.0	м					
	Sector coupling	s					
	Energy storage in modern power grids	S					
	Battery storage	S					
torage	Power storage without batteries						
ergy s	Gas storage, e.g. for storing hydrogen						
E	Hot water storage						
	High temperature heat storage including Power2Heat	s					
_ 2	СНР						
Energy. ficieni	Heat pumps	s					
ef –	System technology for energy efficiency	ME					

Figure 2: Subjects and universities that create the content (green) or use the content (yellow)

4. Development of the material

The material produced until now is mainly videos with greenscreen technology, videos with light-boardtechnology, screencast tutorials and guided Python-simulations. In case of videos with greenscreen technology the speaker stands in front of a green screen during the video production, afterwards the green screen is exchanged by the prepared power point slides. Figure 3 shows a video production in Camtasia.



Figure 3: Production of a teaching video in Camtasia.

Due to the license requirements of CC-BY-SA the power point slides shown in the videos have been completely redesigned. All graphics were created from scratch in order to be able to distribute them under the CC-BY-SA-license.

In Figure 4 four exemplary screenshots of produced videos are shown. The two videos on the left side are produced using the greenscreen-technology. In the video at the bottom right, the speaker was filmed directly in front of a presentation wall. In the video at the top right the picture and the text was drawn via a tablet while the speaker gives an explanation orally.



Figure 4: Screenshots of produced teaching videos

5. Quality assurance

In the beginning, the project consortium agreed on common quality standards, which are appropriately safeguarded in all quality assurance measures. This includes that every content is checked in terms of content and didactic by at least one peer. Criteria were defined for this review, which are then checked by the peers. These criteria include, for example, questions about the understanding and traceability of the teaching materials, as well as questions about the speed of speech and the length of the videos. In addition, all content modules are checked

for formal quality criteria (e.g. sensible font size, general comprehensibility) by a defined group of project employees.

At the moment the materials are used in courses for the first time. The materials are then evaluated by students using evaluation sheets that were created within the project.

6. Use of the teaching / learning offer

The resulting materials are designed in such a way that they are suitable for use by lecturers in courses as well as enabling students to catch up on the content or learn the content independently, for example to prepare for a laboratory or exam.

At the moment the materials are used in courses for the first time in different scenarios. Thereby suitable and current scenarios and methods are tested in teaching practice. The exchange of experiences about the use of the materials in teaching practice is an integral part of the collaboration and flows into general use as iteratively improved material (subject content and methods). In the sense of flipped classrooms, for example, the material can be used for preparation, while questions and topics can be discussed in more depth in face-to-face events in person or online.

A declared aim of the teaching materials is to enable other lecturers in the same subject to use and develop them further. Lecturers can use the modular components of the subject content in self-designed teaching-learning scenarios. On the one hand lecturers can directly use the produced videos or part of the videos in their own courses, on the other hand they can use the PowerPoint slides of the videos and adapt them. This means that all the advantages of innovative, digital teaching and learning concepts can be used for the individual university and target group. Additionally, lecturers can use the materials to supplement their own lectures with additional content and thus make use of the full expertise of the respective university professors.

At the moment, the project consortium is gaining initial experience with the reusability of teaching material by other lecturers. It became clear that very good metadata is important for teaching videos. As a result, lecturers who use other people's material can quickly and efficiently find suitable videos for their own course from a large pool of materials without having to watch all of the videos. Furthermore, short teaching videos are very beneficial, so that the users of the materials can put together their own course from short sequences. In addition, it is helpful to not only provide the videos, but also the associated PowerPoint slides. This means that users of the teaching materials can e.g. simply further develop graphics. In this way they also have the basis to supplement the teaching videos with additional aspects if necessary.

7. Conclusion

The project partners agree that OER creates a high level of added value. There is agreement in the consortium that the quality of the teaching materials has increased compared to previously existing teaching materials. On the one hand, this is due to the mutually enriching exchange in the consortium on content-related and didactic topics as well as legal issues and technical implementation. On the other hand, the project-internal quality control leads to high-quality teaching materials. This is a basic requirement for the material to be available worldwide, freely and permanently on the Internet. The users of OER can therefore benefit from the expertise of the creators and receive teaching materials of high quality.

8. Acknowledgments

The authors would like to thank the "Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen" for funding the project.

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