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AIR-PVT IN SOLAR COOLING SYSTEMS: A FEASIBILITY STUDY

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Summary

While water-based Photovoltaic-Thermal (PVT) systems dominate research due to thermodynamics, Air-PVT offers advantages for integration to buildings, like no leakage risk and easier installation. This paper explores Air-PVT for cooling, where demand aligns with solar generation. Possible applications of Air-PVT include regenerating desiccant wheels in evaporative cooling or nighttime radiative cooling. A TRNSYS model of an Air-PVT prototype is validated experimentally, with next steps involve the modeling of a combined Air-PVT desiccant cooling system, a nighttime radiative cooling system. The study aims to assess their feasibility as concepts, identify critical operation insights and evaluate the prospective for primary energy savings by using Air-PVT for cooling—a novel approach compared to water-PVT and heating-focused studies.

Keywords: Air-PVT, Photovoltaic-Thermal, Desiccant cooling

1. Introduction

About 75% of the building stock in the European Union is currently energy inefficient and it is likely that more than 85% of today's buildings will still be in use in 2050 (European Environment Agency, 2024). EU policy discussions regarding energy renovations are often dominated by the need to reduce greenhouse gas (GHG) emissions. Studies indicate that the share of total building energy consumption allocated to cooling is projected to grow from 2% in 2012 to between 8% and 9% by 2050 (Kranzl et al., 2019). An analysis of the 32 European Environment Agency member countries from 1980 to 2020 indicates that heatwave events resulted in 77,000 to 129,000 fatalities, constituting approximately 86% to 91% of all deaths attributable to climate-related extreme events (European Environment Agency, 2021). It is therefore clear, that cooling will play a critical role in the future, yet sustainable solutions are not widespread so far. To address this gap, this paper details the investigation of the feasibility of solar cooling, where cooling is provided from a renewable energy source, namely the sun, leading to the reduction or even elimination of GHG emissions.

Photovoltaic Thermal (PVT) collectors cool the surface of PV panels, with cooling mediums ranging from air to phase change materials, while harnessing the heat which would otherwise be wasted. As such, PVT is a hybrid system, generating electrical and thermal energy. The heat can be reused for other applications, mainly space heating and ventilation. However, regions with high annual solar irradiation typically exhibit higher cooling needs throughout the year, yet literature has not sufficiently investigated this aspect of PVT in such circumstances. (Guo et al., 2017) described in their study the potential of utilizing PVT for solar cooling applications, specifically desiccant cooling and dehumidification. Their analysis indicated that the temperature level requirements for low temperature desiccant cooling can be met by PVT generated thermal output. Based on previous research (Aspetakis et al., 2025), air will be selected as the cooling medium in this instance, due to the inherent advantages for building installation.

While installations of Photovoltaic-Thermal (PVT) collectors are steadily gaining traction throughout the world, the vast majority of components and systems focus exclusively on water based solutions. Air-PVT

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systems, which utilize air as the heat transfer medium instead of water, had initially development and implementations that has since collapsed, mainly due to subsidies being withdrawn (Weiss and Spörk-Dür, 2024) . As such, water-PVT has been the go-to component to connect to building energy systems, given its superior thermodynamic properties, in order to achieve savings in greenhouse emissions and energy related costs. It is however the conviction of the authors that Air-PVT exhibits strong benefits regarding installation on buildings and the coupling to their energy systems. This is primarily due to the lack of leakage risk, which is a core priority to property owners, as well as the simplified installation procedure among other advantages. So far, research dedicated to Air-PVT has naturally put emphasis on heating systems, usually in the form of either direct space heating or coupling with Air-Source Heat Pumps. This is a favorable scenario mostly for regions with significant heating loads and sufficient solar irradiation during the heating season, which in turn is not a common occurrence. On the other hand, regions with high annual solar irradiation typically exhibit higher cooling need throughout the year, yet literature has not sufficiently investigated the aspect of Air-PVT in such circumstances. In this paper, the authors aim to explore how Air-PVT can potentially assist in covering the cooling loads of buildings, where strong synergy is possible, since the cooling demand and the energy generation are synchronous. Different configurations might be suitable for such applications. Among them, the heated airflow from the Air-PVT can be used to regenerate the desiccant wheel used in desiccant evaporative cooling. Another instance is that of nighttime radiative cooling, where Air-PVT can radiate heat away into the cloudless night sky, providing cooled airflow to buildings.

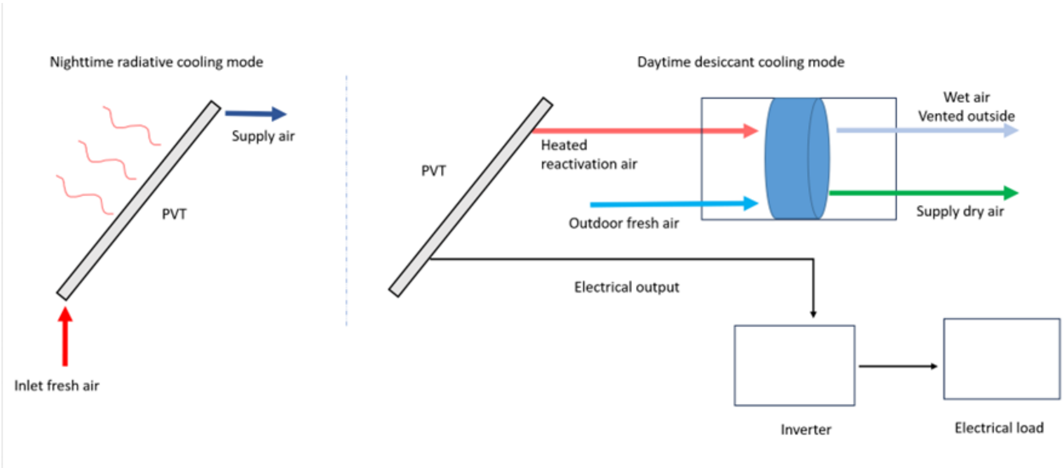


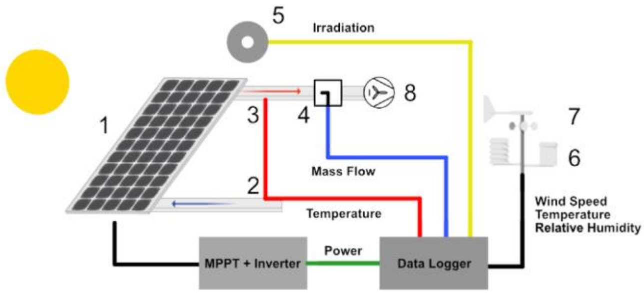
Fig. 1: Illustration of Air-PVT night-time radiative cooling and desiccant cooling system concepts.

2. Overall Scope

The end goal is to assess the feasibility of the aforementioned concepts, provide some understanding into which characteristics are vital for operation and estimate whether primary energy savings can be achieved in building energy systems. The novelty of the investigation lies in that Air-PVT are studied instead of the more established water-based and instead of investigating only heating, cooling loads are taken into consideration. In the end this would be a way of fully utilizing the thermal operation of Air-PVT during cooling season. Air-PVTs, a decentralized renewable energy source, can accelerate sustainable growth worldwide and are associated to the UN’s Sustainable development goals 7 and 11 which concentrate on the production of clean, affordable energy and sustainable cities respectively.

3. Method

For this study, an air-cooled PVT prototype was constructed by sealing the rear of a standard PV panel with a backplate, creating an channel for airflow. Insulation was added to reduce heat losses to the environment. Ambient air was drawn through this channel via an air blower after the collector by inducing negative pressure. The system was installed outdoors on a fixed-angle mount, pictured in Figures 2 and 3. Data collection over a 42-day summer period included temperature, utilizing high-accuracy Pt-100 resistance temperature sensors with 0.2 K uncertainty, airflow, measured with a Pitot tube and pressure transducer and solar irradiance using pyranometers. Wind speed and ambient conditions such as the barometric pressure were also recorded. The panel's electrical output was maximized by utilizing an Maximum Power Point Tracking (MPPT) inverter. All instruments were calibrated on the spot (for example ice bath for temperature sensors) or were shipped pre-calibrated to ensure accuracy. All the instruments utilized are listed in Table 1.



1. PVT collector
2. Inlet Temperature
3. Outlet Temperature
4. Flow Meter
5. Pyranometer
6. Ambient Measurements
7. Anemometer
8. Fan

Fig. 2. Illustration of testing rig.

Fig. 3. Photograph of testing rig.

Tab. 1: Measuring instruments utilized in the experiment, detailing measurement location, type of sensor, brand and accuracy.

Measurement	Location	Type	Sensor	Accuracy
Temperature	Inlet Flow/Ambient	Pt-100 RTD	JUMO Etemp	±(0,1+0,0017 * T) K
	Outlet Flow			
Mass flow	Outlet Flow	Diff. Pressure+ Pitot Tube	KIMO CP212-HO-R	±0.5% of reading ± 2 Pa
Irradiance	Parallel to PV Surface	Pyranometer	Kipp & Zonen CM11	±2%
PV Electrical	PV Output	Inverter	In-house built	±1%
Windspeed	Close to PV Surface	Cup Anemometer	Thies Clima WT	±0.5 m/s
Datalogger	-	-	Campbell CR1000X	±(0.04% of reading + offset)

Night-time Radiative Cooling

The measurements were ongoing on a 24 hour basis and as such data is available for the effect of nighttime radiative cooling. The sample rate was 30 seconds, which leads to quite dense data collection. Based on that monitored data, an assessment of the nighttime radiative cooling potential is performed. The effect of wind and cloud coverage is assessed as well in order to ensure the cause of the cooling is the radiation towards the clear night sky. The cooling rates of the Air-PVT are calculated by Equation 1, where q is normalized heat in W, $\dot{m}$ the massflow rate in kg s^{-1}, c_p the specific heat in J kg^{-1} K^{-1}, T air temperature in K and A the area of the solar panel.

$$q = \frac{\dot{m} C_p \Delta T}{A_{PVT}} = \frac{\dot{m}_{airflow} C_p (T_{outlet} - T_{inlet})}{A_{PVT}} \quad \text{(eq. 1)}$$

Desiccant Cooling

Desiccant cooling systems are typically comprised of two counter flows with a desiccant wheel for the humidity transfer, a sensible wheel for heat transfer between the dry outlet of the desiccant wheel and the cooler return flow (or ambient air), as well as evaporative coolers. The whole process depends on the continuous regeneration of the desiccant wheel, which is normally provided by a low grade heat source, such industrial waste heat or solar thermal energy. An example of such a unit is illustrated in Figure 4.

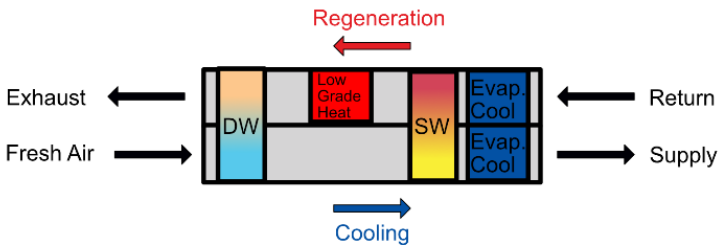


Fig. 4. Typical desiccant cooling configuration.

In this investigation the potential of utilizing Air-PVT as the low grade source of heat. In this instance the components remain the same with the addition of a PVT section and a post heater that is used to ensure target regeneration temperatures are reached. The PVT section can either be a direct pass through Air-PVTs or through the use of an air-to-air heat exchanger, yet that would increase costs and decrease heat transfer rates. Since that is counterintuitive to the goal of utilizing cheap, low temperature heat, it has been decided to take the first approach, although the second one is still feasible. The configuration in that case is shown in Figure 5.

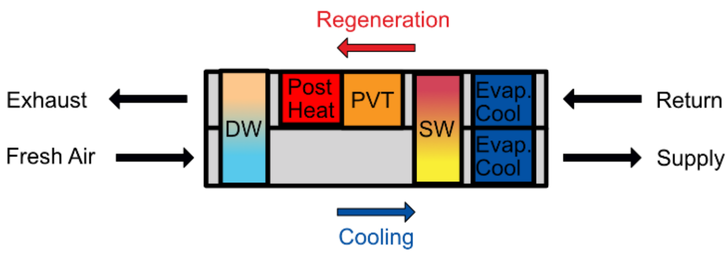


Fig. 5. Air-PVT desiccant cooling configuration.

A second configuration was considered as well, due to the location of the PVT within the unit, after the sensible heat exchange. Since that airflow is heated already before it reaches the PVT, it is detrimental to the cooling of the solar panel and that results in reduced electrical generation. Therefore it can be potentially beneficial to instead utilize two different airflows, one for the PVT and one for cooling down the dried supply air. This configuration, presented in Figure 6, is modelled in order to assess this impact on performance.

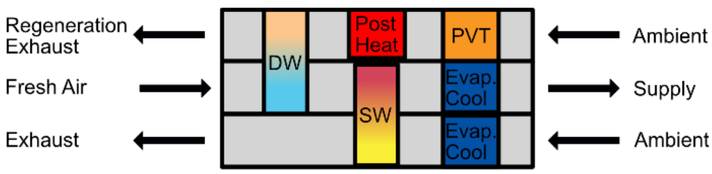


Fig. 6. Alternative Air-PVT desiccant cooling configuration.

In all instances, the post heater is powered by the electrical production of the photovoltaic panel, with a setpoint of 55 °C, which is the most common regeneration temperature in desiccant cooling systems on the market (mostly supplied by district heating or waste heat). This target is however not reached necessarily with lower production. However, that is not problematic, the desiccant cycle can operate at lower temperatures as well, with reduced moisture removal.

To assess the feasibility of the Air-PVT collector in solar desiccant systems, a simulation model was developed in TRNSYS software and utilized the measurements of the experimental testing rig described above. The process included gathering data and developing a model of an desiccant evaporative cooling system where the regeneration of the desiccant wheel is facilitated with the heated airflows of the Air-PVT, illustrated in Figure 1, equipped with a post-heater to top up outlet temperatures when required levels are not reached. Electrical generation supplies power to the operation of the cooling cycle, the after-heating and the grid according to conditions. The modelling and validation procedures of the Air-PVT are described in a previous study by the authors (Aspetakis and Wang, 2025). It was shown that the outlet temperature depends on the massflow of air coming through every collector. In this instance the default operating massflow has been set to 90 kg/h of air through each collector, with other rates examined later in the analysis. The calculations of the desiccant are based on equations developed by (Jurinak, 1982) for silica gel:

$$T = \left(\frac{2865}{4.344\omega^{0.8624} - F1} \right)^{\frac{1}{1.49}}$$

$$T = 6360\left(F2 + 1.127\omega^{0.07969} \right)^{\frac{1}{1.49}} \qquad \text{(eq, 2 \& 3)}$$

Therefore, to explore the feasibility and potential of Air-PVT in desiccant cooling systems the following configurations are simulated, compared and evaluated:

- Regeneration air is preheated before Air-PVT section.
- Regeneration air is ambient air intake.
- Configurations with different massflow rates are considered.

Component	**TRNSYS Type**	**Parameters**
Experiment Data	Data reader Type 9	42 days, 30 sec resolution
Thermodynamic Properties	Psychrometrics Type 33	-
Post Heater	Electric Heating Coil Type 930	Power from PV Data
Desiccant Wheel	Rotary Desiccant Dehumidifier Type 1716	εF1=0.157 εF2=0.965 (Martínez et al., 2017)
Sensible Wheel	Sensible Air-to-Air Heat Recovery Type 760	η=0.75
Evaporative Cooler	Evaporative Cooling Device Type 506	η=0.9
Air-PVT	Un-Glazed Building Integrated Photovoltaic System Type 569	Calibrated and validated in previous study (Aspetakis and Wang, 2025)

4. Results

Night-time Radiative Cooling

The daily radiative cooling effect during the entire operation of the experimental Air-PVT is shown in Figure 7. Values range from 0 to 600 kJ/m²/night. In order to determine whether wind and clouds had any significant effect on the cooling generated, a scatter plot of wind speeds and cloud coverage for varying cooling rates was created and presented in Figure 8.

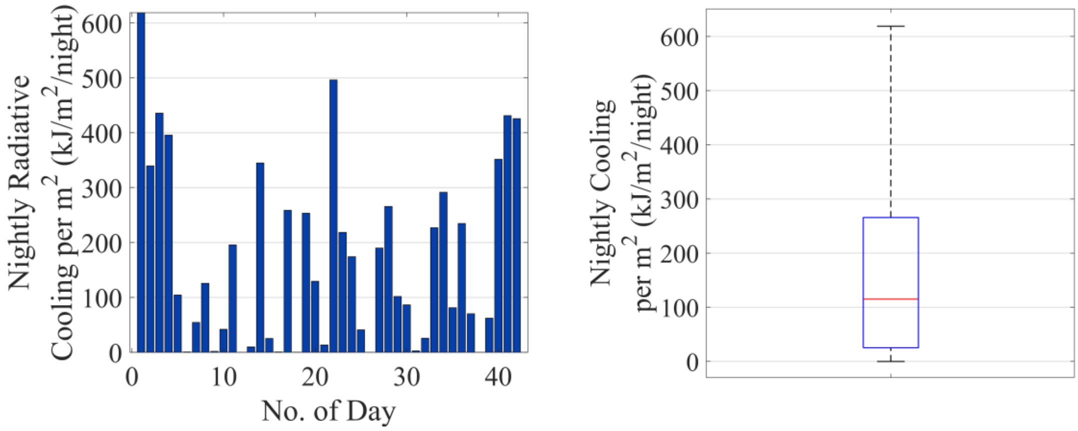


Fig. 7. Daily Cooling per square meter trend and boxplot for the duration of the test.

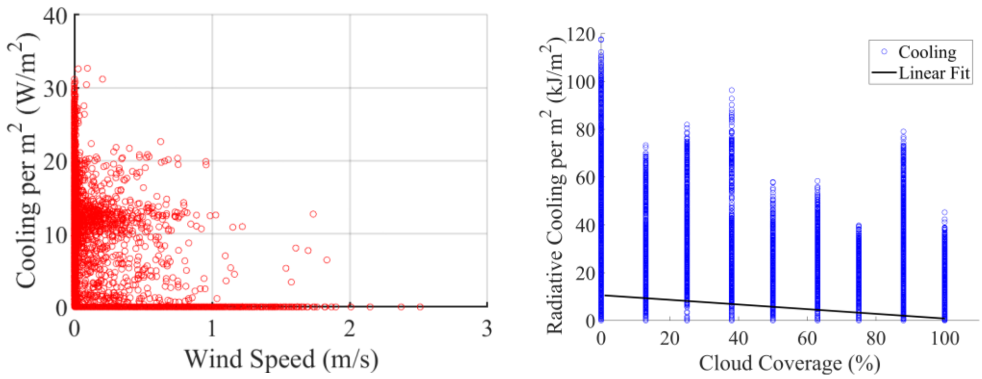


Fig. 8. Scatter plots of windspeed rates and cloud coverage for varying levels of cooling.

Desiccant Cooling Configurations

At a first stage, the temperatures generated by the Air-PVT in testing, are displayed in Figure 9, to determine the extent of the heat load that can be covered by solar gains. It is evident that only the preheating configuration is able to reach the design temperature of 55 °C, with the aid of the post heater, supplied by PV generated electricity. The configuration with no preheating before the PVT is still operates, with lower efficiency. The preheating configuration managed to reach the design temperature consistently. The daily electrical generation of the two configurations per m² is shown in Figure 10, in the form of the daily production bars and a boxplot of the distribution. It can be determined that the power production is decreased, with poorer performance from the preheating configuration, as expected. However this difference is not significant as displayed by the boxplot. Concerning cooling, the daily sensible cooling generated per m² is shown in Figure 11. Due to the higher median and broader range of the distribution, the preheating configuration is able to drive the desiccant process with higher temperatures and therefore provides higher cooling than the non-preheating one. Over the course of the period, days without any cooling can be observed, which can be attributed to either overcast weather or no need of cooling, on colder days. Median achieved cooling was 167 and 137 kJ/m²/day but turned to 753 and 710 kJ/m^2/day when omitting overcast and cold days.

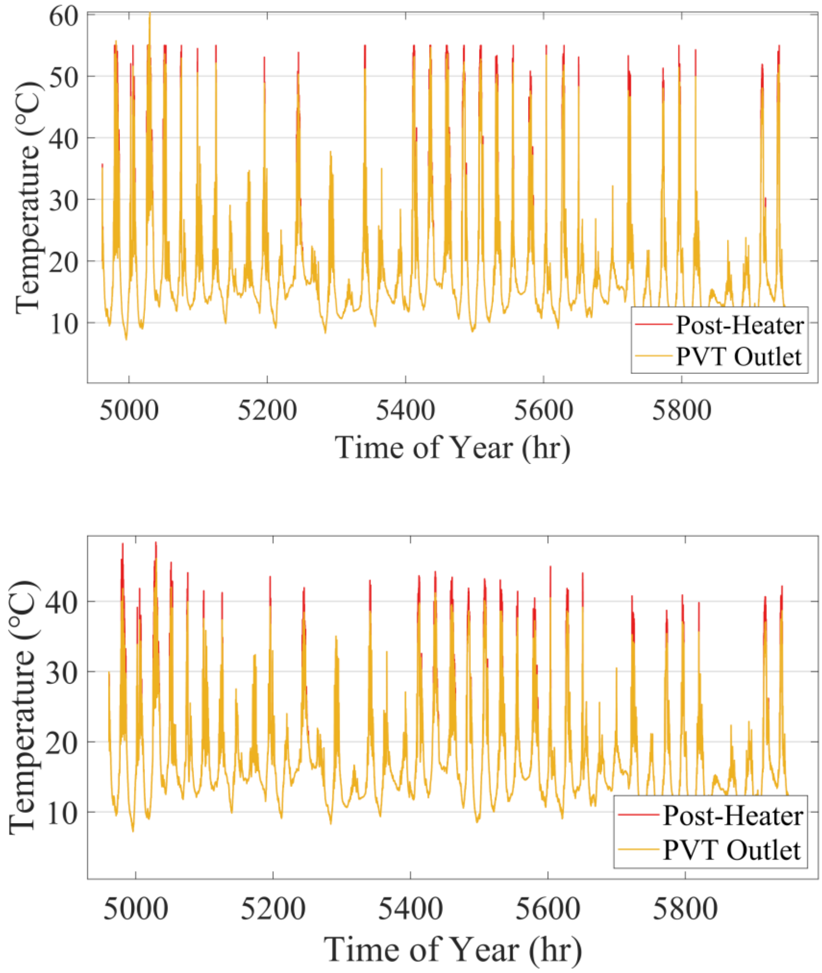


Fig. 9. Temperature Outlets of Air-PVT and Post Heater for (a) preheating and (b) no preheating configurations.

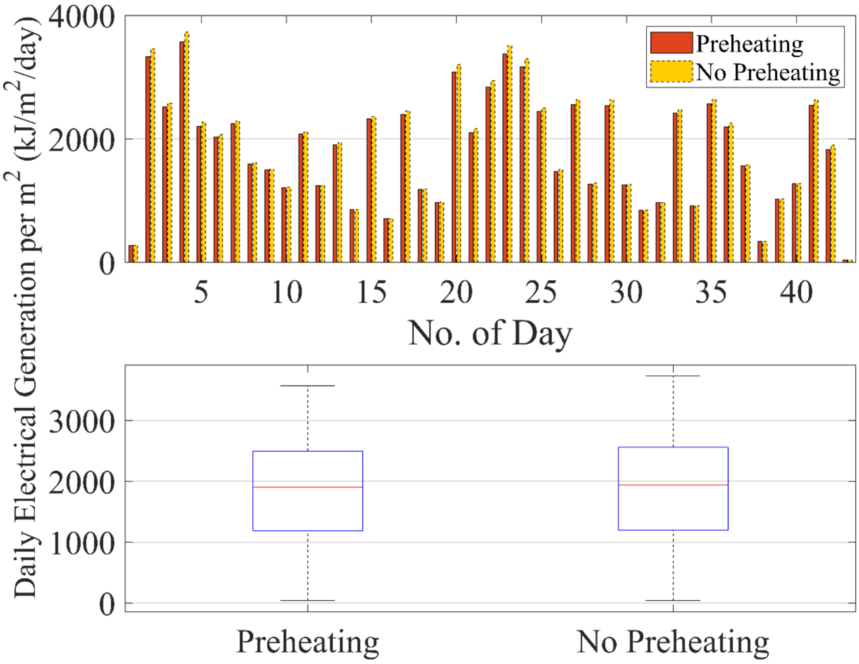


Fig. 10. Daily Electrical generation per m^2 for preheating and no preheating configurations.

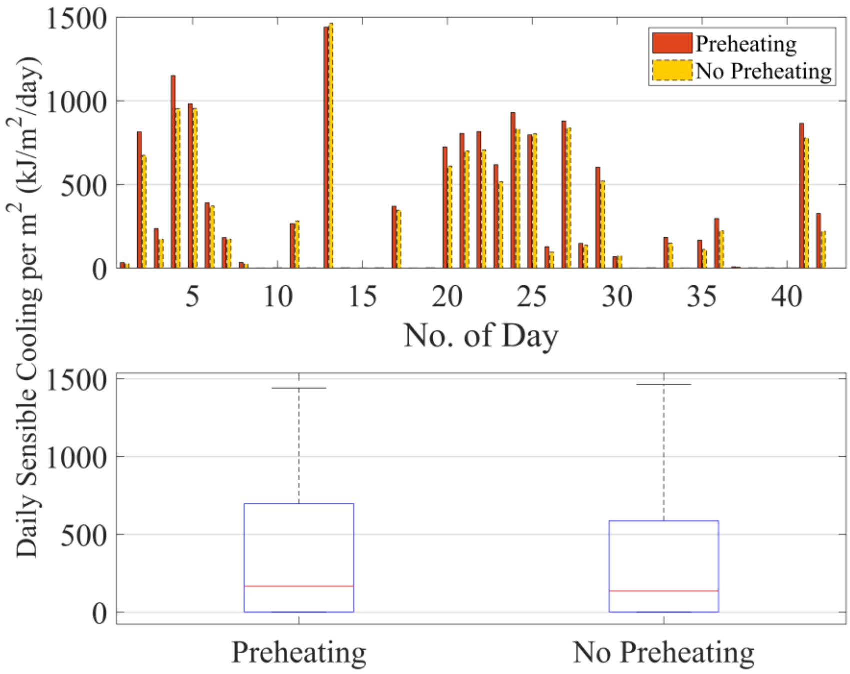
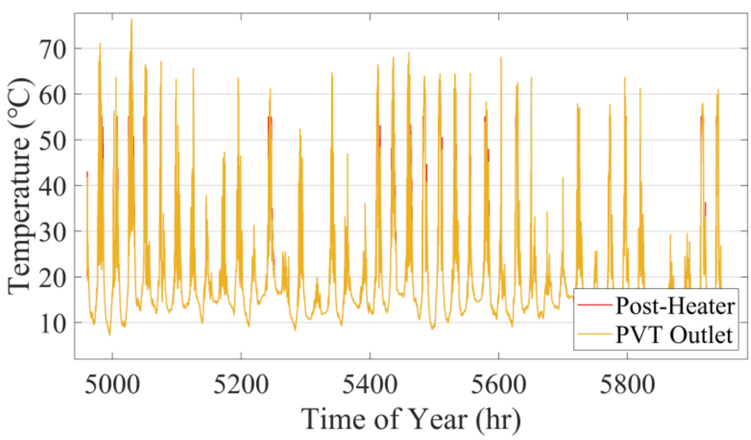


Fig. 11. Daily Sensible Cooling per m^2 provided for preheating and no preheating configurations.

Effect of massflow

The temperature outlet are presented in Figure 12, for a lower massflow rate. In this instance, the non-preheating variation is capable of raching the design temperature setpoint with the aid of the PV-powered post heater. In the case of the preheating configuration, even higher temperatures are obtained, up to 70 °C in some cases. In Figure 13 the electrical generation is presented, with the same trend to be found, of reduced generation by the preheating variation. At this stage, the decrease of electrical production between the two flowrates needs to be noted, with median of 1902 and 1940 kJ/m^2 for 90 kg/h while for 45 kg/h the generation was 1883 and 1931 kJ/m^2 respectively. The solar cell modules are not as cooled down in the sencind iteration which results in reduced electrical output, albeit not significantly. For the case of cooling provision, pertinent rates are displayed in Figure 14. A similar tendency is detected in this occasion as well, in regards to the difference of preheating and non-preheating variations, as well as a reduction of the cooling for the 45 kg/h case, despite the higher temperatures flowing through the desiccant wheel. That is naturally the result of the decreased massflow through each collector which affects the cooling power.



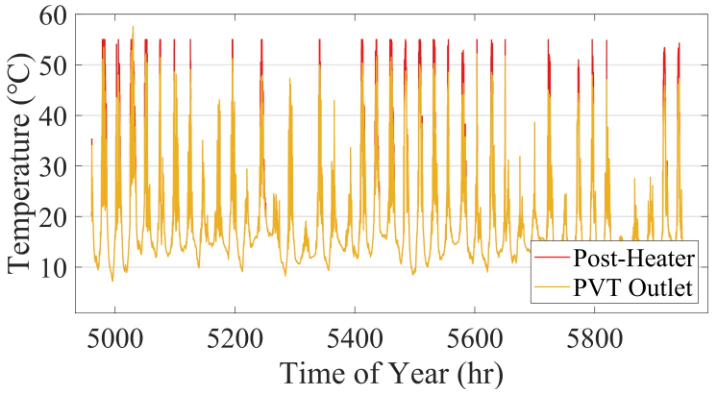


Fig. 12. Temperature Outlets of Air-PVT and Post Heater for (a) preheating and (b) no preheating configurations at 45 kg/h.

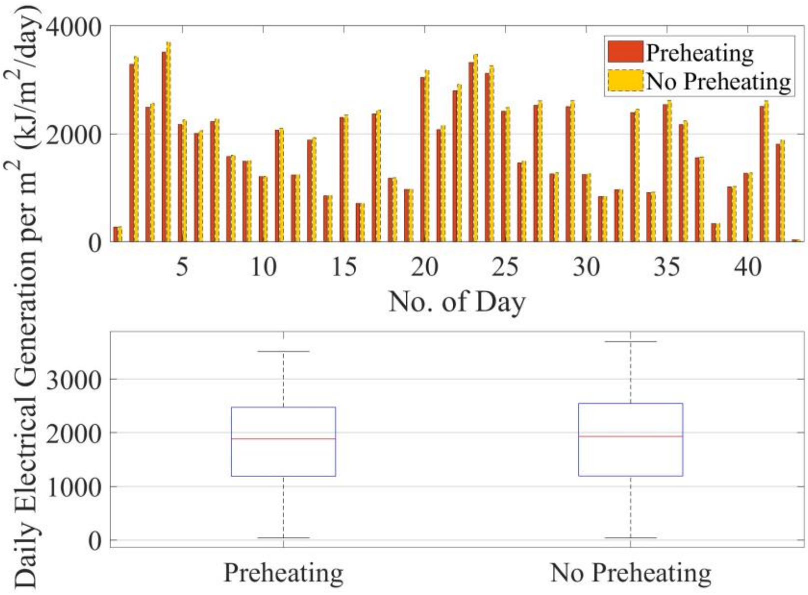


Fig. 13. Daily Electrical generation per m^2 for preheating and no preheating configurations at 45 kg/h.

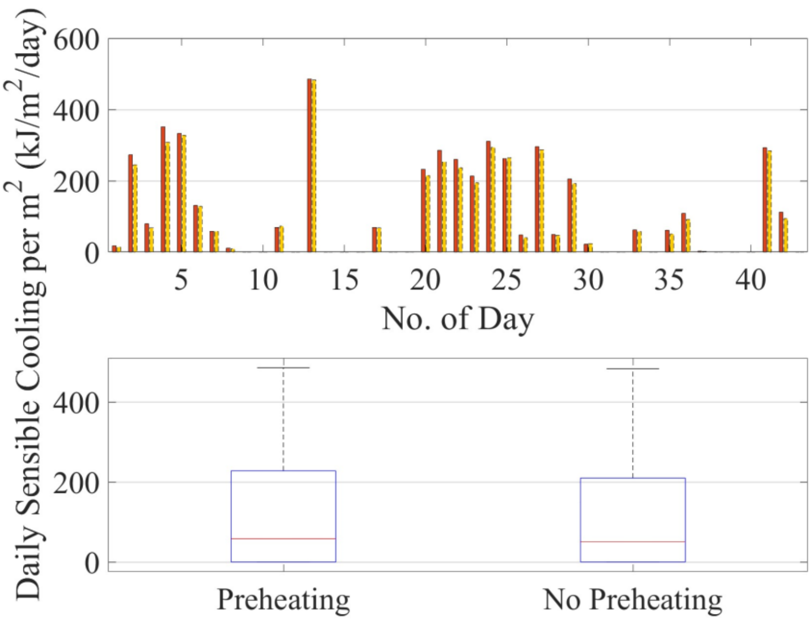


Fig. 14. Daily Sensible Cooling per m^2 for preheating and no preheating configurations at 45 kg/h.

5. Discussion

Results for the analysis of the radiative cooling demonstrate that it varies markedly throughout the testing period. It is primarily influenced by the sky cloud coverage, being blocked on overcast nights, rather than wind. Radiative cooling can be considered as a form of free cooling since no direct consumption or conversion of energy is taking place, apart from the fans for blowing air. The cooling rates exhibited in this study suggest that radiative cooling from Air-PVT solar fields should not be neglected but rather incorporated into energy system designs.

As for Air-PVT desiccant cooling, the findings indicate that the standard solar desiccant configuration with the addition of the Air-PVT section does indeed lower the generation of electrical power of the solar cells, compared to the ambient intake variant, yet only marginally, while providing higher cooling rates. It is therefore, an inherent trade-off between the thermal and electrical energy supply. The type of implementation will be based on the characteristics of the application, or the priorities of the designer. Since the losses on the electrical side are not significant, the thermal gains are noteworthy and the layout follows a standard design, the preheating configuration is recommended for Air-PVT solar cooling systems. Furthermore, this is beneficial because existing desiccant cooling systems can be retrofitted with an Air-PVT pass instead of manufacturing an entire unit from start again.

The analysis of the effect of the massflow reveal that decreasing the rate leads to higher air temperatures flowing through the desiccant wheel and at the same time lowers the available power of the cooling flow. In the design phase to ensure elevated temperatures levels and subsequently safeguard stable operation, yet would potentially require larger solar fields since the cooling power per area is reduced. As such, facilities with more available installation area might benefit from such arrangements while facilities with limited space might opt for smaller solar fields with higher airflow per collector.

6. Conclusion

Based on experimental testing with an air-based Photovoltaic Thermal prototype and energy simulations, the feasibility of two cooling concepts utilizing Air-PVTs was explored, namely free cooling from nighttime radiation and solar desiccant cooling.

- Radiative cooling can be highly stochastic and measurements indicated a median of 115 kJ/m^2/night (32 Wh/m^2/night)
- Radiative Cooling rates were primarily affected by cloud coverage, wind had minimal effect.
- Median desiccant cooling was 167 and 137 kJ/m^2/day (753 and 710 kJ/m^2/day when omitting overcast and cold days) for the preheating and non-preheating configurations respectively and can reach up to 1500 kJ/m^2/day for climatic conditions of this experiment.
- For desiccant cooling systems, preheating the incoming airflow to the Air-PVT reduces electrical energy generation but leads to higher cooling rates.
- The massflow through each Air-PVT collector significantly influences the regeneration temperature and cooling power.

Future investigations will potentially involve experimental data from real desiccant wheels on the market as well as explore Air-PVT desiccant cooling in different regions and climates, with higher ambient temperatures and solar irradiance.

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8. Acknowledgements

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NOMENCLATURE AND SYMBOLS

Quantity	Symbol	Unit
Photovoltaic Thermal	*PVT*	
Photovoltaic	*PV*	
Irradiance	G	W m^{-2}
Humidity ratio	ω	
Heat flux	q	W m^{-2}
Mass flow rate	$\dot{m}$	kg s^{-1}
Specific heat	c	J kg^{-1} K^{-1}
Area	A	m^2