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OPTIMIZING THERMAL MANAGEMENT IN PHOTOVOLTAIC PANELS: EXPERIMENTAL STUDY

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Abstract: This study investigates the enhancement of thermal management in photovoltaic (PV) systems by implementing a modified setup with copper pipes and an aluminium-based adhesive to boost thermal conductivity. Conducted over a four-month period at the Hungarian University of Agriculture and Life Sciences, the research examined the impact of varying cooling flow rates, insulation levels, and inlet temperatures on the working temperature of a modified PV system. Findings demonstrate that full insulation significantly raises working temperatures up to 67%, while lower inlet temperatures and increased cooling flow rates effectively decrease them to 11,54% and 18,97% respectively. The results suggest that optimizing thermal management can enhance PV efficiency in high-temperature environments, promoting the system's resilience and efficiency in diverse climatic conditions.

Keywords: photovoltaic systems, radiation, insulation, inlet temperature, flow rate

1. Introduction

As the global demand for sustainable energy continues to rise, solar photovoltaic (PV) technology remains a vital component of the renewable energy landscape. However, the efficiency of PV systems is significantly influenced by various environmental factors, particularly temperature. Managing these factors effectively is crucial for optimizing the performance of solar cells and maximizing energy output. Typically, solar panels are produced under standard test settings (STC). These parameters specify that for every one degree increase in temperature, the efficiency of the PV panel decreases by 0.004-0.005 % [1]. Al-Ghezi et. al. investigates the impact of solar radiation and operational temperatures on photovoltaic (PV) panels, employing both PVsyst simulation software and outdoor experiments [2]. The results indicate that elevated operating temperatures have a detrimental effect on the performance of the panels. Specifically, a 1°C rise in temperature leads to a slight increase in current (approximately 0.068%), but results in a decrease in voltage (around 0.34%), output power (about 0.489%), and efficiency (approximately 0.586%). And the other hand Ale et. al. demonstrates that the temperature of PV modules, along with various other elements, significantly influences the performance of PV systems [3]. Additionally, it establishes a strong and positive linkage between module temperature and key performance indicators, including solar irradiance, short circuit current, output power, and conversion efficiency.

Tripathi et. al. investigates the impact of solar radiation and ambient temperature on the temperature of solar PV panels [4]. The experiments were carried out in Telangana, India, specifically during the sunny days of February 2020. The studies have confirmed that higher temperatures can reduce the efficiency of a panel and potentially harm its cells when exposed to lengthy periods of elevated temperatures. The high level of accuracy observed indicates the model's efficacy in forecasting panel temperatures. Specifically, the panel temperature reached 78.50°C when exposed to solar radiation of 1140 W/ m^2 and an ambient temperature of 36°C. Continued exposure to such high temperatures can have a negative impact on the performance and structural integrity of the panel. Many previous researches have investigated the possibility of using solar energy in domestic hot water production [5], [6], [7]. The results of these researches have often had difficulties in storing and utilizing heat produced at low temperature levels at higher temperature levels. Han et. al. also examines the electrical and thermal performance of two solar energy systems, a combined Photovoltaic-Thermal (PVT) system with a Solar Thermal (ST) system (PVT-ST), and a separate Photovoltaic (PV) system with a Solar Thermal (ST) system (PV-ST) [8]. The research examines the effectiveness of these systems under varied environmental variables, such as varying levels of solar radiation, ambient temperatures, and inlet water temperatures, by developing a detailed heat transfer model. The results indicate that the PV-ST system demonstrates exceptional performance in situations with lower ambient temperatures and solar radiation. This is attributed to its effective cooling mechanism, which improves its electrical efficiency. In contrast, the PVT-ST system demonstrates superior performance in situations with elevated ambient temperatures and intense solar radiation. This is due to its efficient combination of photovoltaic and thermal elements, resulting in increased electro-thermal efficiency and primary energy conservation. Boumaaraf et al. evaluates the performance of a locally manufactured photovoltaic/thermal (PV/T) collector versus a traditional PV module under the climatic conditions of Ghardaia city, Algeria, aiming to address individual housing energy needs in semi-arid regions [9]. A detailed mathematical model incorporating heat transfer balance equations, along with electrical and thermo-physical properties, was developed and converted into a numerical program within the MATLAB environment for theoretical simulations and experimental validations. The findings reveal that the PV/T collector demonstrates a slightly higher electrical efficiency of 7% compared to 6.78% for the PV module, alongside a remarkable thermal efficiency of 61% and an overall efficiency of 79.43%. Boumaaraf et al. embark on an investigative journey to transform a conventional photovoltaic (PV) panel into a photovoltaic-thermal (PVT) collector, with the aim of enhancing both electrical and thermal energy production [10]. Outdoor experiments were conducted, and a data collecting system based on a personal computer (PC) was used to assess the effectiveness of the system. The findings revealed a marginal increase in electrical energy production by 0.32% and a notable gain in thermal energy with an average efficiency of 20.33%. However, it was observed that the PVT collector's moderate thermal insulation considerably impeded its ability to generate thermal energy. Several studies have also investigated the use of solar energy in the food industry [11], [12], [13], but these studies have not addressed the optimal solution to the simultaneous demand for heat and electricity.

The determination of the temperature of photovoltaic cells is a distinct and captivating issue, as the effectiveness of converting solar radiation into electrical energy is contingent upon it. Various research has examined different methods of cooling photovoltaic (PV) modules, highlighting the importance of maintaining ideal operating temperatures to improve efficiency and avoid harm. The hybrid PVT (HPVT) system combines a PV module and a traditional thermal collector into a single piece of equipment, allowing for the simultaneous availability of both thermal and electrical energy. Despite extensive research on thermal management in PV systems, the concept of "heat capacity" has remained largely unexplored in this context. Recognizing this gap, my research aims to systematically compare the heat capacity of conventional and modified PV systems. The study involves continuous modifications to a PV system, with the goal of minimizing its working temperature, consequently, maximize its ability to maintain stable temperatures and high electrical output under hot weather conditions.

2. Material and methods

In this experiment, we worked with both a conventional PV panel and a modified version that has copper pipes attached with a specialized aluminium adhesive to boost thermal conductivity. By tweaking factors like the cooling flow rate, insulation, and inlet temperature, we aimed to find the best setup to maximize the system's heat capacity. Using sensors, we closely monitored temperature changes, sunlight intensity, and electrical output, all with the goal of developing a PV system that can maintain or even improve its efficiency as temperatures climb ultimately enhancing solar energy performance.

2.1. Material

The experimental setup used to evaluate the impact of heat capacity improvements on photovoltaic (PV) systems, The experimental setup includes a standard PV panel and a modified version (Figure 1.). The modified panel features copper pipes adhered to its backside (Figure 2.) using a Synthetic Resin adhesive containing 75% aluminium (Figure 3.) with different thicknesses (3 to 5 mm). The system also includes adjustments to the flow rate of the cooling medium to optimize heat removal. As well as XPS Insulation (20 mm) to minimize heat loss and maintain effective temperature control. Central to our experimental setup is the Arduino-based control unit (Figure 4.), which plays a critical role in orchestrating data acquisition and real-time monitoring of the PV systems. This robust platform interfaces seamlessly with a network of strategically placed sensors throughout the systems. The system includes a 10-liter thermal storage tank (Figure 4.), which plays a crucial role in the cooling process of the modified PV-T panel. This tank is designed to hold and manage the cooling fluid, ensuring a stable and consistent supply for the cooling system. Our system is equipped with a Perion 95 Ah battery which serves as the primary electrical storage solution. This high-capacity battery is essential for storing the electrical energy generated by the PV systems, ensuring that power is available for use even when sunlight conditions are less favourable. With its substantial 95 Ah capacity, the Perion battery offers robust performance and reliability, supporting extended periods of energy storage and usage.

Figure 1. Experimental Setup, Conventional PV and modified PV panels

In our experimental setup, a network of carefully chosen sensors is employed to monitor and optimize the performance of both the conventional and modified PV systems. These sensors play a vital role in capturing real-time data, which is crucial for evaluating system behaviour and effectiveness. The LM335 temperature sensor was used to provide precise temperature readings at various points in the system, offering reliable accuracy within 1°C over a broad range. To measure solar irradiance, we used the TF 6003.0000 BG irradiance sensor, which captures global radiation with a silicon diode and PMMA dome perfect for photovoltaic applications and useful in fields like climate research and agriculture. For current measurement, the ACS712 sensor handled both AC and DC currents by translating them into a proportional voltage. Lastly, a 10:1 voltage divider was employed to scale down voltages for safe monitoring by the Arduino, providing essential data on the system's electrical output and efficiency.

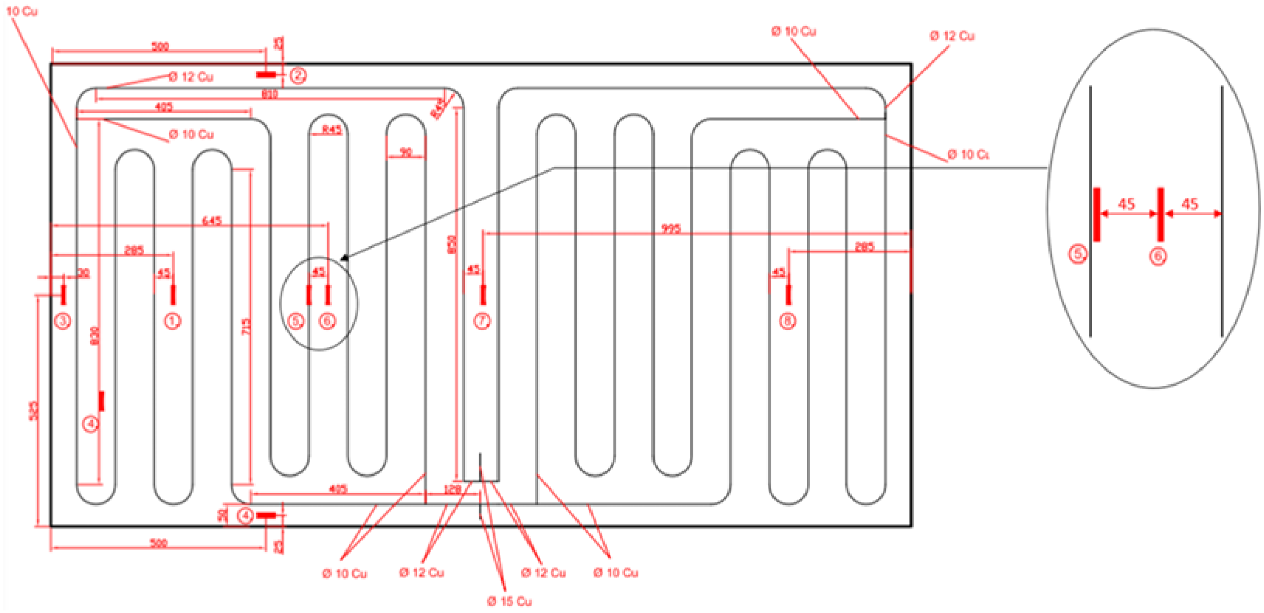

Figure 2. Cooling system and Temperature sensors distribution

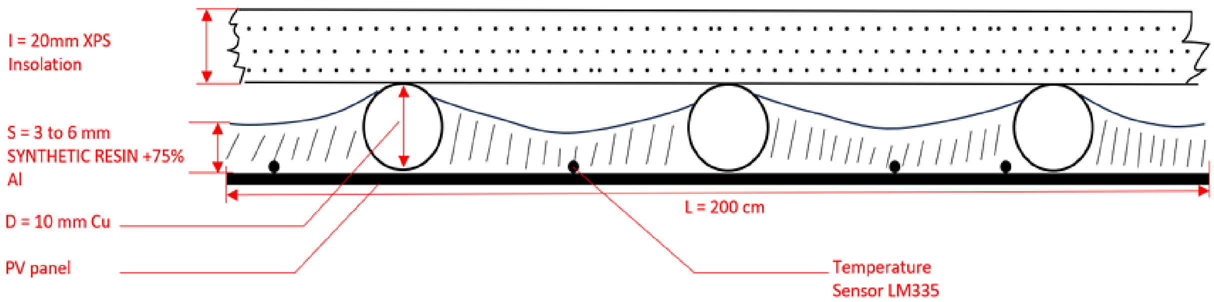

Figure 3. PVT module design cross section

Figure 4. Arduino-based control unit and the storage tank

2.2. Methods

The experiment was conducted over a four-month period (June, July, August and September 2024) in the energetic building's laboratory at the Hungarian University of Agriculture and Life Sciences from 10:00 AM to 04:00 PM. The experimental setup includes a modified PV system equipped with copper pipes adhered to the backside of the panel using a specialized adhesive material containing 75% aluminium. This setup is designed to enhance thermal conductivity and improve cooling efficiency. By incrementally adjusting variables such as cooling flow rate, insulation, inlet temperature, the study seeks to identify the optimal configuration for achieving the highest possible heat capacity in a PVT system. Throughout this process, an array of sensors is used to monitor temperature variations across different components of both the modified and unmodified PV systems, as well as other critical parameters like irradiance, ambient temperature, and electrical output. The ultimate goal is to develop a PV system capable of maintaining or even improving electrical production in the face of rising temperatures, thereby pushing the boundaries of solar energy efficiency.

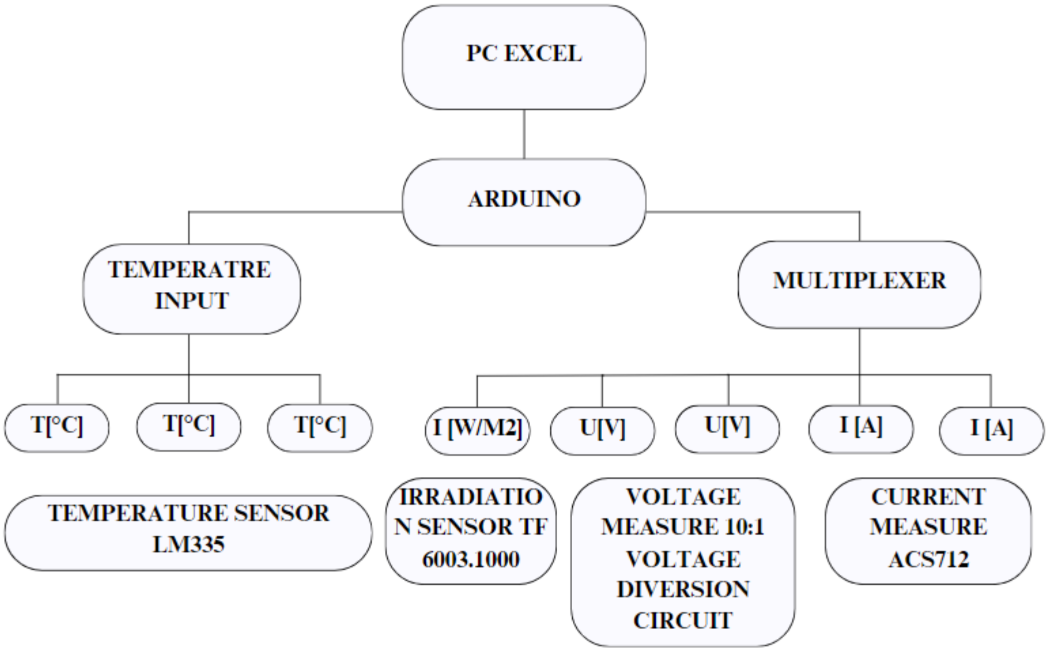

Figure 5. Data acquisition Architecture

3. Results

For the purpose of this analysis, data from 10 selected days were chosen to examine the primary objectives. The results focus on the impact of system insulation, as well as the effects of inlet temperature and cooling flow rate. By analyzing these critical variables, we aim to understand how modifications impact the working temperature of the modified photovoltaic panel.

3.1. Insulation effect

To analyze the impact of insulation on the modified PV panel's temperature Table 1. shows a comparison of the working temperature of the modified PV panel with that of the unmodified panel, under similar conditions, including irradiation, ambient temperature, flow rate, and inlet temperature. With full insulation, the modified PV panel consistently exhibits significantly higher working temperatures than the conventional PV panel. In mostly sunny conditions (Figure 6.), the modified PV panel's temperature is about 67% higher than that of the conventional PV (Figure 7.), while under mostly cloudy weather, it is approximately 63% higher. This indicates that the full insulation retains more heat within the modified system, amplifying its working temperature.

Table 1. Impact of PV system insulation during sunny and cloudy weather conditions.

Date	Periods	Ts [°C]	Q [l/min]	Insulation	T amb [°C]	PV-T [°C]	PVT-T [°C]	G [W/m2]	Weather
19 June	Morning	15	4	Full	26.28	27.34	43.68	778.10	Mostly sunny
	Noon				27.85	30.52	52.25	966.77	
	Afternoon				30.13	31.32	53.55	924.13	
14-Aug	Morning	15	7	No	33.52	39.51	31.77	823.26	Mostly sunny
	Noon				36.22	42.64	34.28	914.45	
	Afternoon				40.70	41.56	33.44	751.13	

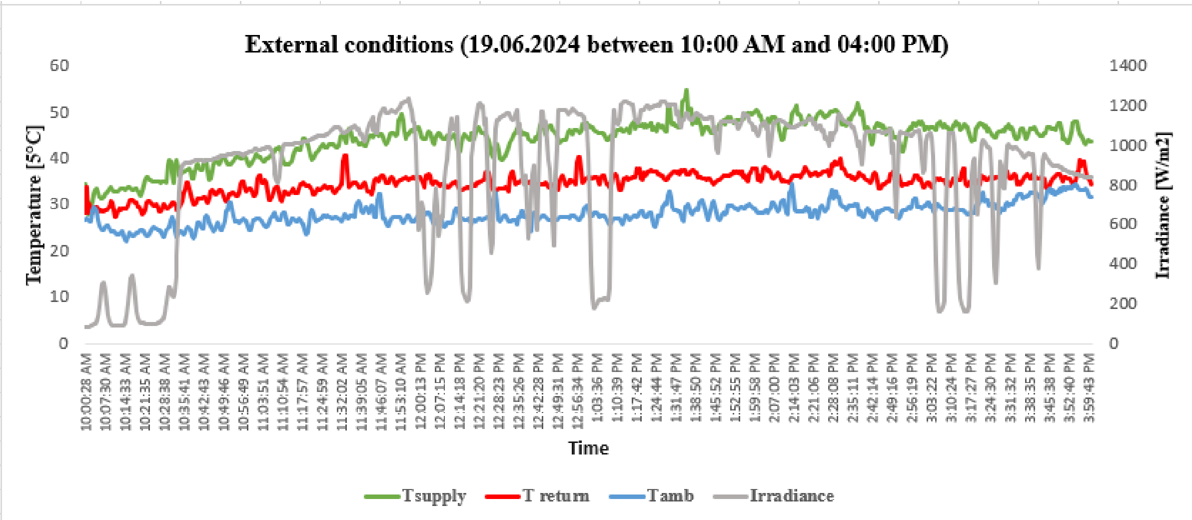

Figure 6. External Condition and the ON state of the system insulation

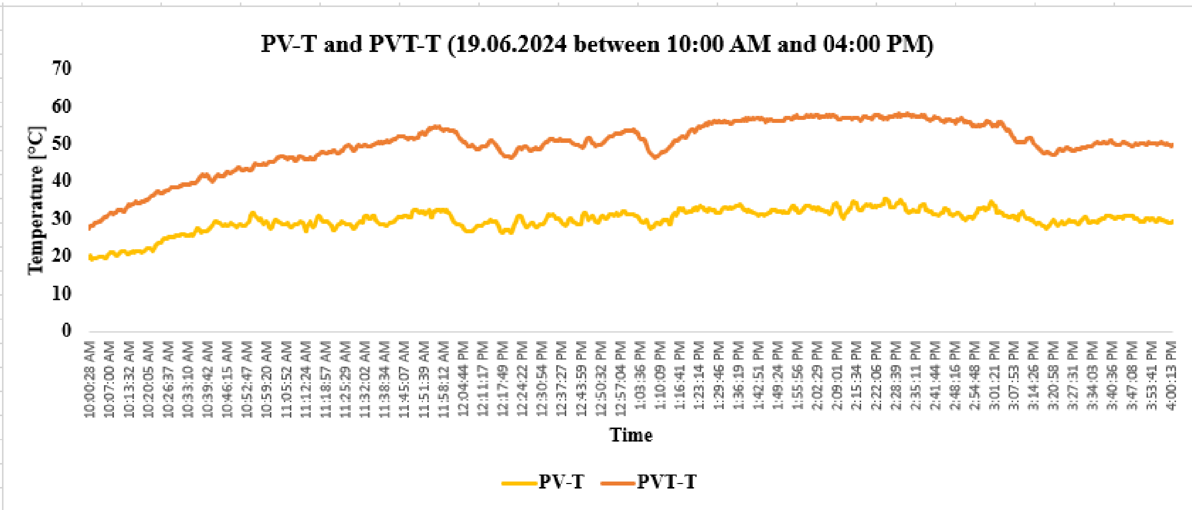

Figure 7. PV-T and PVT-T while the ON state of the system insulation

However, when the insulation is removed, the modified PV panel experiences a substantial temperature reduction. Specifically, the temperature decreases by around 19.58% during severe weather conditions (Figure 8.) and by approximately 21.82% in mostly cloudy weather (Figure 9.). This indicates that the absence of insulation allows for better heat dissipation, significantly lowering the working temperature of the modified PV panel. Overall, insulation has a substantial impact on increasing the working temperature of the modified PV panel, particularly under more extreme weather conditions.

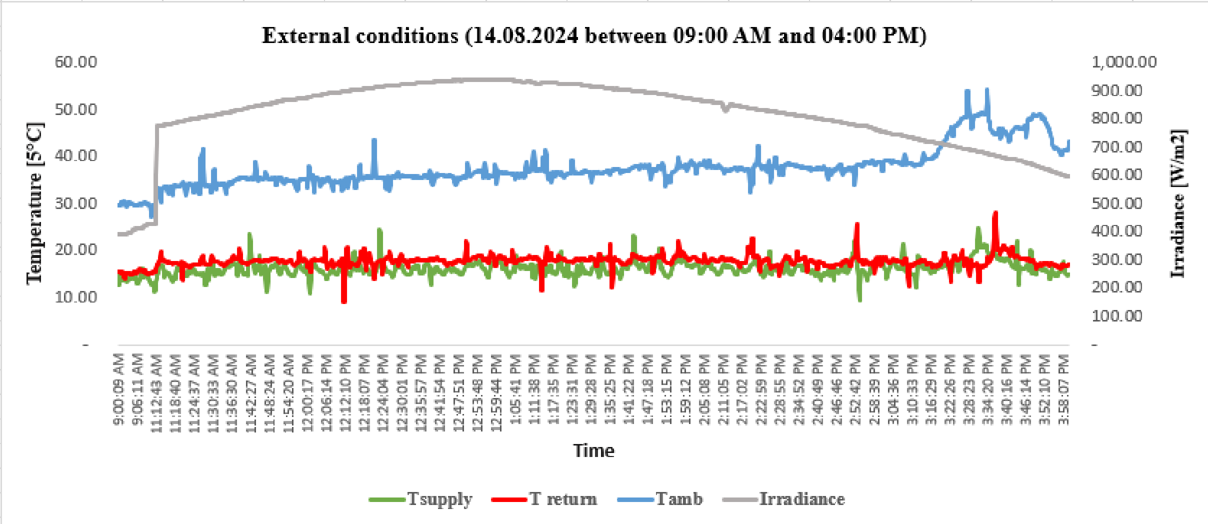

Figure 8. External Condition and the OFF state of the system insulation

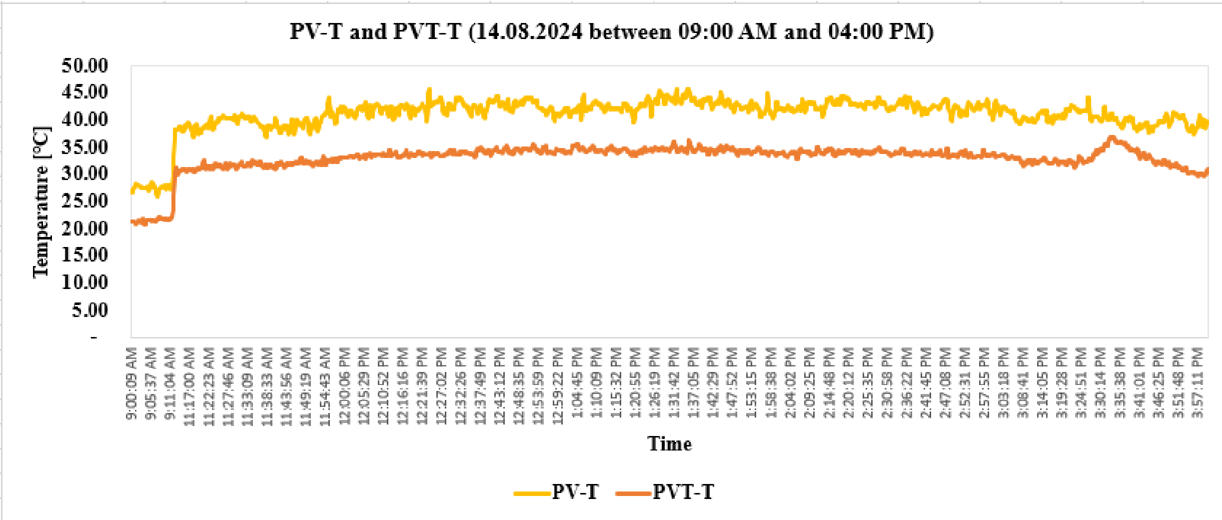

Figure 9. PV-T and PVT-T while the OFF state of the system insolation

3.2. The impact of the inlet Temperature

Table 2. illustrates the impact of inlet temperature on the working temperature of the modified PV panel by comparing the temperature difference between the PV-T and PVT-T systems. This comparison was made under consistent flow rate conditions (4 l/min) and similar external conditions over three sunny days (20 June, 7 July, and 3 July). For a clearer assessment of the inlet temperature's effect, all selected days reflect conditions where the modified PV panel was fully insulated.

Starting with the non-cooling state on 20 June (Figure 10.), where the inlet temperature was not set, the working temperature of the modified PV panel (PVT-T) was 64.4% higher than that of the conventional PV panel. When the cooling system was activated and the inlet temperature was set to 10°C on 7 July (Figure 11.), this temperature difference decreased to 34.32%, indicating a significant cooling effect. Furthermore, with an even lower inlet temperature of 8°C on 3 July (Figure 12.), the difference was reduced to a more desirable level of 11.54%. These results highlight the substantial impact of lower inlet temperatures on reducing the working temperature of the modified PV panel when fully insulated.

Table 2. PV-T and PVT-T under different inlet temperatures.

Date	Periods	Cooling state	T_s [°C]	Q [l/min]	Insulation	T_{amb} [°C]	PV-T [°C]	PVT-T [°C]	Weather
20-June	Morning	NO	NO	NO	Full	28.01	25.89	40.10	**Mostly sunny**
	Noon					30.10	29.77	50.95	
	Afternoon					31.61	29.81	49.82	
7-Jul	Morning	C	10	4	Full	28.68	22.39	30.14	**Mostly sunny**
	Noon					33.71	26.53	35.51	
	Afternoon					31.57	24.22	32.58	
3-Jul	Morning	C	8	4	Full	27.61	17.36	19.60	**Mostly sunny**
	Noon					30.38	18.86	21.42	
	Afternoon					31.13	27.67	29.92	

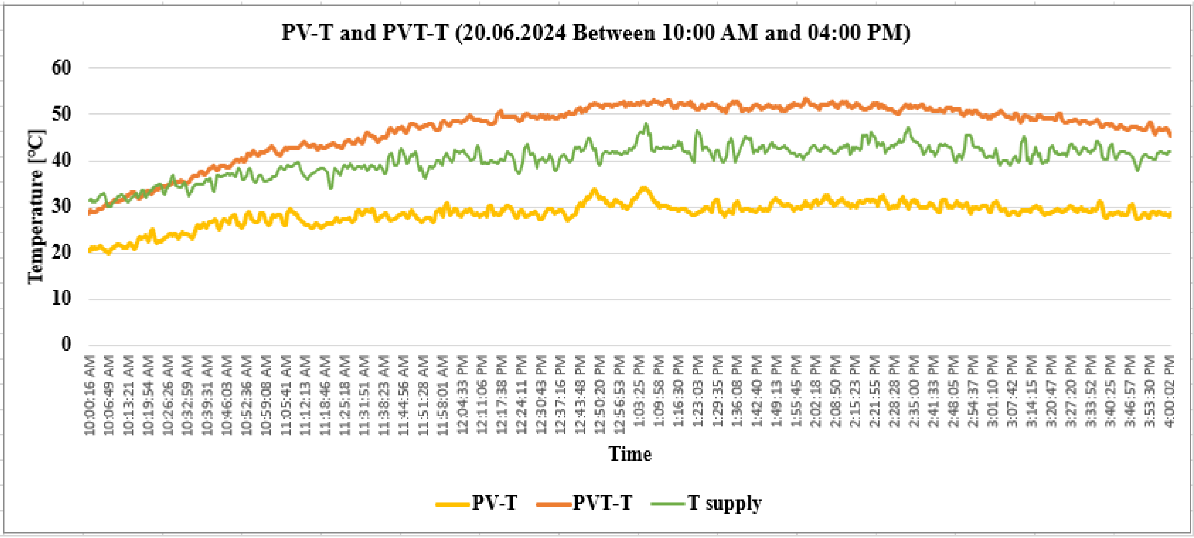

Figure 10. PV-T and PVT-T while the cooling system is OFF

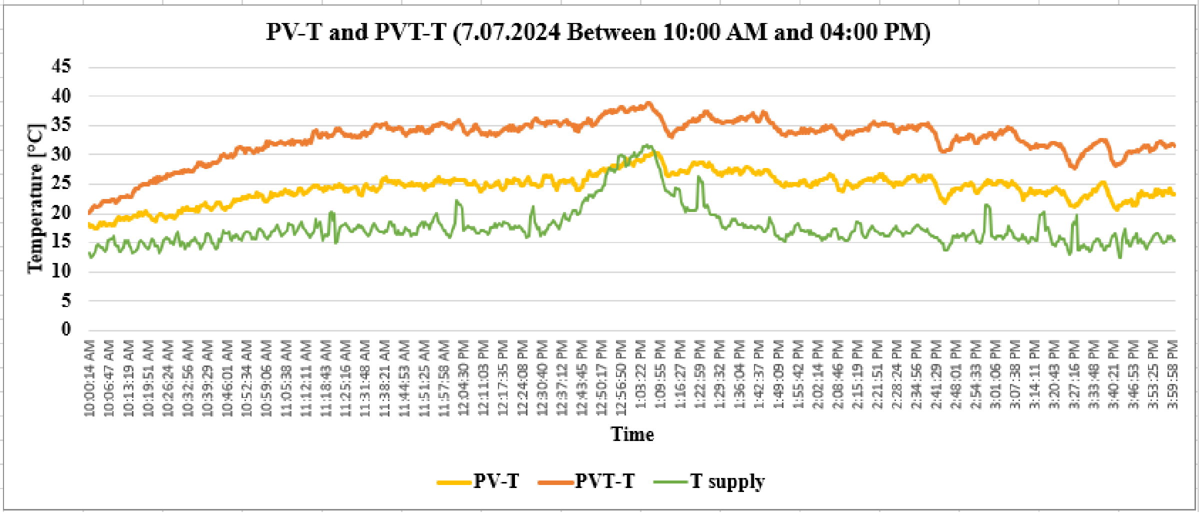

Figure 11. PV-T and PVT-T with an inlet Temperature of 10°C

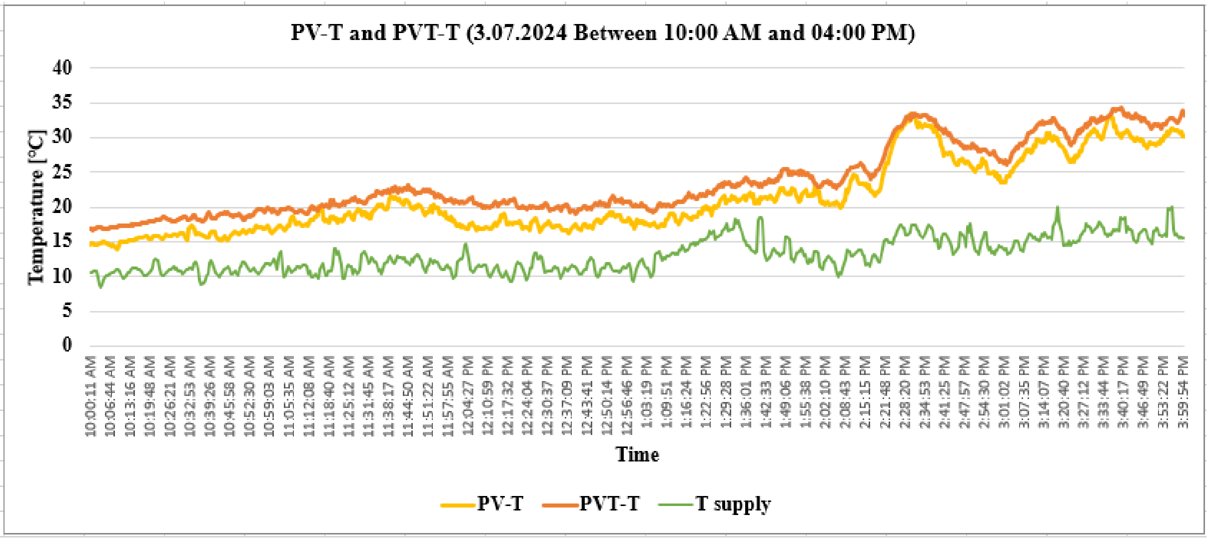

Figure 12. PV-T and PVT-T with an inlet Temperature of 8°C

3.3. The volum flow rate effect

Table shows the impact of flow rate on the working temperature of the modified PV panel compared to the conventional PV panel, under similar weather conditions and ambient temperatures. For this analysis, we selected four sunny days with no insulation applied to the modified PV panel (31 August, 1 September, 19 September, and 20 September). Two different flow rates were tested: 4 l/min and 7 l/min. To assess the real impact of flow rate, we used a lower inlet temperature with the lower flow rate and a higher inlet temperature with the higher flow rate, based on previous findings that lower inlet temperatures generally lead to a lower working temperature for the modified PV panel. For the lower flow rate (4 l/min) with an inlet temperature of 10°C on 19 and 20 September (Figure 13.), the PVT-T system operated only 7.65% and 6.43% lower than the PV-T, respectively, despite the favorable inlet temperature and lack of insulation.

Table 3. PV-T and PVT-T under different flow rate conditions.

Date	Periods	T_s [°C]	Q [l/min]	Insulation	T_{amb} [°C]	PV-T [°C]	PVT-T [°C]	G [W/m^2]	Weather
19-Sep	Morning	10	4	No	21.55	21.32	19.19	562.83	Mostly sunny
	Noon				25.71	29.69	28.05	874.34	
	Afternoon				25.84	26.50	24.53	694.14	
20-Sep	Morning	10	4	No	20.68	21.25	19.39	584.22	Mostly sunny
	Noon				25.12	29.08	28.00	911.65	
	Afternoon				25.75	26.63	24.82	716.30	
31-Aug	Morning	15	7	No	27.97	35.40	28.00	646.57	Mostly sunny
	Noon				31.68	42.20	35.63	891.72	
	Afternoon				34.41	34.86	27.73	493.53	

Conversely, when the flow rate was increased to 7 l/min, even with a higher inlet temperature of 15°C on 31 August and 1 September (Figure 14.), we observed a more substantial cooling effect. Here, the working temperature of the PVT-T system showed a reduction of 18.97% compared to the PV-T on 31 August and 17.46% on 1 September. These results highlight that, although a lower inlet temperature improves cooling, a higher flow rate has a more pronounced impact on reducing the working temperature of the modified PV panel, even with a higher inlet temperature and no insulation.

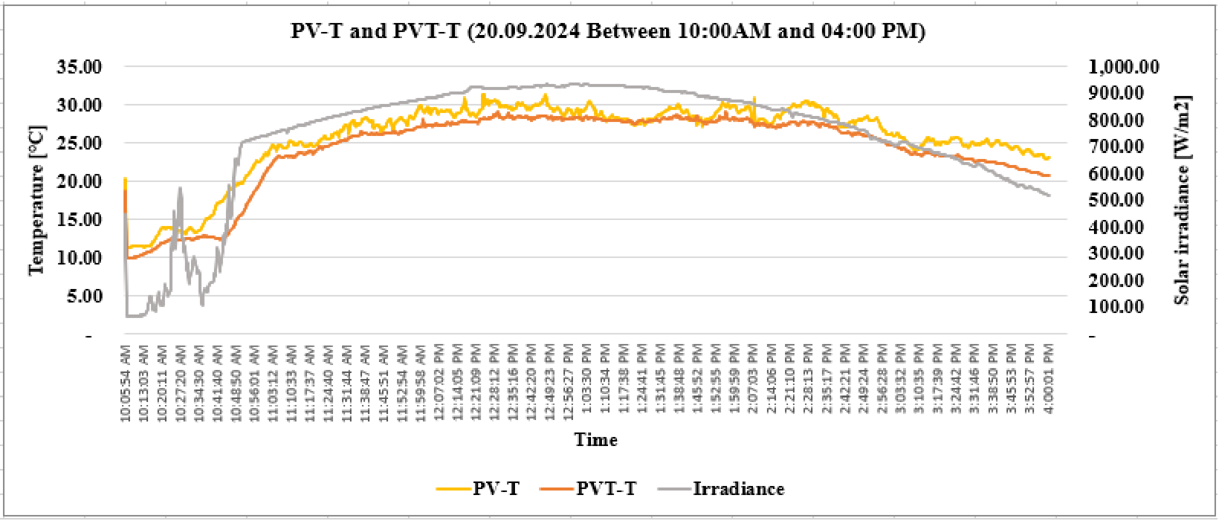

Figure 13. PV-T and PVT-T under flow rate of 4 *l*/min

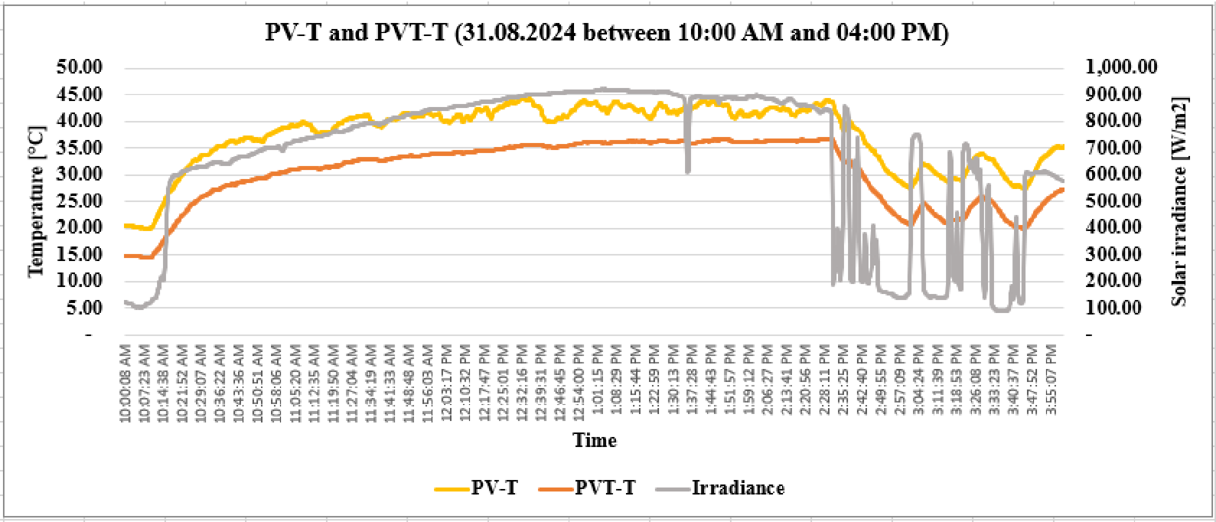

Figure 14. PV-T and PVT-T under flow rate of 7l/min

4. Conclusions

This study highlights how crucial thermal management is for photovoltaic panels. It shows that solar panels designed with better heat dissipation techniques can work more efficiently in high temperatures. Through careful experiments, researchers found that both insulation and cooling methods are key in controlling the temperatures and efficiency of solar systems. As previously has been investigated in other researches, heat capacity can be of great importance for solar energy systems, and in the present research we have focused on this area [14], [15].

Interestingly, while full insulation can help retain heat, it also leads to higher temperatures in the panels, which isn't ideal for performance. On the other hand, lowering the inlet temperature and increasing the flow rate proved to be effective in keeping temperatures down.

The results suggest that a balanced approach to thermal management, combining insulation and cooling, can significantly enhance the durability and efficiency of solar panels, especially in hot climates. The modified panels were able to maintain cooler operating temperatures, making them suitable for areas with strong sunlight.

This research not only adds valuable insights into how we manage heat in solar technology but also paves the way for more studies on improving heat dissipation techniques and materials for better solar panel performance in various climates. Combined with the results of other research, optimal removal of recovered heat is found to be feasible even with the addition of heat pump systems [16], [17].

5. Acknowledgement

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