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Research Article

Performance analysis of flow channel collector for photovoltaic thermal system

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Abstract. Solar energy has seen the most significant development in the past decade. Electricity and hot water production are the two most common uses of solar energy. A photovoltaic (PV) system is a popular method for generating electricity from solar energy. However, PV systems are known for their low efficiency, which reduces further as the PV cell temperature rises. The photovoltaic-thermal (PVT) system combines a PV system with a thermal collector to provide dual benefits, namely power generation and hot water production. However, PVT system research often employs a constant flow (CF) strategy in which water is continually cycled throughout the experiment, making it inapplicable. In comparison, the constant collection temperature (CCT) scheme is a more feasible approach, but its impact on PVT system performance has received less attention. This study compares a flow channel PVT system using both CF and CCT strategies. The results show that the CF scheme achieved a higher maximum thermal efficiency of 35.05%, while the CCT scheme reached 17.89%. The CCT method can also maintain the optimum water temperature despite changing radiation circumstances. The PVT system outperforms traditional PV panels regarding electricity efficiency, with a maximum improvement of 0.89% and 0.96% utilizing the CF and CCT schemes, respectively. These results show that PVT systems with CCT schemes that use less energy for pumping outperform PV panels in terms of power production and electricity efficiency.

Keywords: solar energy, thermal photovoltaic system, constant flow, constant collection temperature, flow channel, power generation.

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1. Introduction

The periodic increase in energy consumption has stimulated the vast exploitation and development of energy resources. However, climate change and the environmental impact of fossil fuels necessitate the development of renewable energy sources such as solar energy. Photovoltaic (PV) systems are the most popular way to harness solar energy to provide electricity as a dependable renewable energy option (IRENA, 2019). However, solar radiation can cause PV systems to overheat during operation, decreasing their efficiency and lifespan (Hasanuzzaman *et al.*, 2016). A water-based photovoltaic-thermal (PVT) system that cools PV cells while producing hot water is one technique that has been developed to address this issue. As a result, PVT systems could provide the daily electricity and hot water needs for the residential and industrial sectors. However, only a few studies of PVT systems have addressed how to keep the produced hot water temperature stable and the implications for system performance.

Through many developments and research initiatives, PVT system performance has improved significantly over the years. A. K. Tiwari *et al.* (2023) underlined the efficiency of PVT systems in using solar energy for electricity and heat, stressing the need for material selection and the possibilities of laminated PVT systems. (Herrando *et al.*, 2023) expanded on this by investigating various types of PVT collectors, such as dual air-water, heat-pipe, and building-integrated systems (BIPV-T). They emphasize the importance of design optimization, next-generation PV technologies, coatings, and nanofluids in system performance. Jha *et al.* (2023) concentrated on designing and developing heat exchangers in air- and water-based PVT systems. They found that innovations like honeycomb plates and parallel rectangular tubes significantly increase thermal efficiency. Şirin *et al.* (2023) investigated the integration of PVT systems inside building façades of BIPV-T. They address engineering difficulties and the possibilities of advanced materials, such as latent heat storage and PCMs embedded in nanoparticles, to improve performance. A key example of this material and design synergy is presented by Al-Aasama *et al.* (2023), whose PVT collector combined twisted absorber tubes with nano-PCM to achieve a remarkable combined efficiency of 88.86% and a 34.5% boost in electrical efficiency, showcasing the potential of such hybrid enhancements. These studies highlight the ongoing advancements in PVT technology, which are driven by innovative designs, material science, and the integration of new technologies, with the goal of making PVT systems more viable, efficient, and widely adopted.

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The desired hot water temperature for domestic use varies depending on the specific application. For showering and bathing, the recommended temperature falls within the range of 38 °C to 42 °C, while laundry water typically ranges from 30 °C to 40 °C for optimal cleaning (Fuentes *et al.*, 2018). On the other hand, a temperature range of 50 °C to 60 °C suffices for general cleaning purposes, aiding in effectively eliminating bacteria and other microorganisms (Laitala *et al.*, 2011). Additionally, hot water serves various purposes in industrial and agricultural settings, such as cleaning, sanitation, and disease control with 40 °C water (Rawat *et al.*, 2021).

The solar water heater (SWH) system is a common method of supplying hot water demand using solar energy. This system circulates water from the solar thermal collector to a water storage tank. This system relies on additional heaters when the desired temperature is not reached. SWH systems are equipped with electronic controls that regulate the distributed hot water based on the constant collection temperature (CCT) to improve hot water production efficiency. In such scenarios, hot water is produced only at the desired temperature when solar energy is available and stored in an insulated tank until used.

The inclusion of the CCT scheme in SWH systems potentially improves the performance of PVT systems as they serve the same objective of providing hot water (Selvaraj *et al.*, 2023). However, despite the potential benefits of CCT in PVT systems, more research has yet to be conducted on its impact on system performance. The literature has predominantly focused on assessing PVT systems using the constant flow (CF) method, which may not reflect real-world operating conditions. The heat transfer process between the absorbers and the PVT surface is arguably more effective using CCT than the CF method (Mawoli *et al.*, 2020). Thus, this study utilized a novel sinusoidal flow channel PVT system (FC-PVT) to examine its performance under CF and CCT methods.

The flow channel thermal collector is widely recognized as a straightforward configuration in PVT systems. This collector is a narrow duct formed of two metal plates, often called a parallel plate collector (Nahar *et al.*, 2017). Water flows through the duct to absorb heat from the solar cells, allowing for cooling and thermal energy gain. Nevertheless, the adoption and commercial availability of FC-PVT systems still need to be improved. Nahar *et al.* (2017) modeled an FC-PVT system using the CF method in Peninsular Malaysia weather and found that its overall efficiency can reach 84.4%. Their outdoor experiment discovered an overall efficiency of 80%, with 10% electrical and 70% thermal efficiency. Their findings also revealed a potential 9% increase in electrical power and demonstrated a 13°C temperature drop in FC-PVT compared to PV-only systems, from 77°C to 60°C. Furthermore, their modeling predicted a 0.8% increase in FC-PVT efficiency, which was supported by a 0.7% improvement in their experiments.

Dubey & Tay (2013) experimented with FC-PVT using a CF scheme to compare it with sheet and tube PVT systems (ST-PVT). They analyzed the influence of water flow rate variations on their performance. They found negligible differences between ST-PVT and FC-PVT performance, with thermal efficiencies of 40.7% and 39.4% and electricity efficiencies of 11.8% and 11.5%, respectively. Ji *et al.* (2006) investigated the effect of channel collector design on PVT system performance. They discovered that segmenting the flow channel into multiple ducts with equal water distribution was critical to lowering the temperature of the PV cells. Surprisingly, dividing the flow into 30 segments resulted in temperature reductions of up to 5 °C, resulting in a 7% increase in energy efficiency. Additionally, Bashir *et al.* (2018) evaluated FC-PVT systems utilizing monocrystalline (mono-Si) and polycrystalline (poly-Si) PV modules. They found that the average PVT temperature was lower than the PV panel by 13.6% and 7%, leading to increased electrical efficiencies of 13% and 6.2%, respectively.

Regarding parameters affecting the PVT performance, Salem Ahmed *et al.* (2019) found that solar radiation intensity and ambient air temperature were critical weather parameters. Their findings indicated that implementing a water-cooling system resulted in a surface temperature reduction of 20.8% and an electrical power increment of 8% compared to a PV panel. The FC-PVT system exhibited maximum and average overall efficiencies of 76.4% and 68.9%, respectively. Hormozi Moghaddam & Karami (2022) identified that fluid flow rate is another factor influencing FC-PVT performance. They found that an increase in flow rate from 8 L/h to 32 L/h led to a considerable reduction in the surface temperature of PV cells. Advancing this principle, Al-Otaibi *et al.* (2024) showed that optimizing the cooling configuration is equally vital. Their novel irregular-linear jet design achieved a superior temperature reduction of 60.62 K and an overall efficiency of 63.5%, proving that advanced hydraulic layouts are crucial for maximizing the performance gains from higher flow rates.

Furthermore, the application of the CCT approach in PVT systems has been investigated in the literature, but primarily through numerical studies. For instance, A. Tiwari *et al.* (2009) developed a numerical model to predict the water temperature in an integrated photovoltaic thermal solar water heater. They observed that a rise in CCT settings resulted in decreased efficiency. They also concluded that there was an increase in overall thermal efficiency with a high water flow rate, whereas the maximum thermal efficiency was achieved at a flow rate of 0.006 kg/s. Another numerical study of the PVT system was carried out by Mishra & Tiwari (2013) for partially covered (case A) and fully covered (case B) collectors under the CCT scheme. They found that case A is better for thermal energy, with 4167.3 kWh of annual gain. In contrast, case B is better for electricity generation, with a net yearly electrical energy gain of 1377.63 kWh. G. N. Tiwari *et al.* (2018) proposed a thermal model to simulate the operational characteristics of a semitransparent photovoltaic thermal-compound parabolic concentrator using a CCT scheme. They demonstrated that this system can generate a maximum overall exergy gain of 2.44 kWh/m² at a constant collection temperature of 80 °C.

Several experimental investigations have also been conducted on PVT systems employing the CCT scheme. Ceylan *et al.* (2014) evaluated a PV cooling system utilizing a 54-watt PV panel and a spiral thermal collector. Their findings highlighted that implementing cooling resulted in higher electrical efficiencies of approximately 13%, compared to about 10% without cooling. Furthermore, an increase in temperature setting from 45 °C to 55 °C led to a slight decrease in electrical efficiency. However, the higher setting increased the output water temperature, enhancing overall system efficiency. This principle of managing energy trade-offs is further illustrated by Kristi *et al.* (2025), who compared pump control strategies for active water-cooling. They found that while a continuously active pump provided the best cooling and highest raw electrical output, it consumed so much energy that it resulted in a negative net energy gain of -6.21%. In contrast, a smarter PWM-controlled pump, which used less water and energy, achieved a superior net energy gain of 9.94%, despite providing slightly less cooling. This trade-off between water temperature and PV efficiency must be considered because electrical and heat energy cannot be directly compared. Coventry & Lovegrove (2003) argued that Primary Energy Saving efficiency should be applied because electrical power produced by a PVT system is a more effective energy storage medium than water heat energy.

Tashtoush & Al-Oqool (2018) agreed with the significance of the setpoint temperature in PV module cooling. Their experiment also examined the effects of water flow rate and setpoint temperatures ranging from 30 to 50 °C. The results indicated that the cooling system achieved significant excess energy production ranging from 15.28% to 17.75% with minimal water losses. Mawoli *et al.* (2020) proposed PV panel cooling using a CCT strategy that regulates the water flow based on the temperature difference between the rear and front surfaces. A solenoid valve is activated if the temperature difference is less than or equal to 1.5 °C. The system exhibited a mean surface temperature of 49.31 °C, 5.38% lower than the standard PVT system at 54.92 °C. The maximum temperatures for the PV surface were 54.0 °C, compared to 57.6 °C without a cooling system.

The literature review identifies a research gap in PVT systems. Previous research has often been limited to computer simulations or short-term tests, which cannot fully demonstrate long-term system performance in real-world conditions. This study addresses that gap by conducting a long-term, real-world evaluation of a fluid-cooled PVT system. The experiment compares two operating methods: the conventional CF method and a more adaptive CCT method. The key difference is in their operation. The standard CF approach runs the pump continuously, consuming more energy. In contrast, the CCT method is more efficient, activating the pump only when needed to maintain a set temperature. Although CCT has been studied for cooling photovoltaic panels, its performance has not been directly compared to CF in a full PVT system over a long period.

Therefore, the main goal of this work is to fill this research gap. Building on earlier findings that thermal collector design and operating parameters influence PVT system performance (Umam *et al.*, 2022), this research assesses the long-term stability and practical performance of the CCT scheme compared to CF. Over an extended period and under varying weather conditions, the experiment measures key outcomes such as PV cell temperature, electrical power output, and heat collected. This study aims to provide empirical evidence for developing more efficient and practical PVT systems.

2. Methodology

2.1 Experimental setup

This experiment used two identical 250 Wp PV panels, one as a preferred system and the other as a PVT system with an additional heat collector on the back. The dimensions of the PV panel were 1660 x 990 x 30 mm (length x width x thickness). The sinusoidal flow channel thermal collector was fabricated from an aluminium sheet (1220 x 950 x 3 mm), chosen for its high thermal conductivity of approximately 167 W/m·K to ensure efficient heat transfer from the PV module. This was supplemented by three aluminium cover plates (1220 x 270 x 3 mm), as illustrated in Figure 1. A 10 mm thick layer of chloroprene rubber (neoprene), with a low thermal conductivity of about 0.2 W/m·K and a density of 1330 kg/m^3, was used as a spacer and thermal insulator between the plates. The assembly was secured using bolts and nuts to ensure mechanical integrity and good thermal contact. The use of rubber also guarantees appropriate sealing and prevents potential leaks. In addition, four 10 mm half-flat copper tubes were used to connect the three chambers within the collector and enhance water flow. The system utilized water as the sole cooling fluid, selected for its safety and suitability for direct use in residential applications, such as domestic hot water pre-heating. The thermal collector is then attached to the rear side of the PV panel with thermal paste to improve heat transfer to the thermal collector. Also, an insulation layer of 10 mm polyethylene foam was placed on the outermost part of the assembly to reduce heat loss. Iron bars were also installed to keep the collector in place and avoid unexpected shifts.

In order to assess the electrical performance of PV and PVT panels, two programmable DC loads were connected to the junction boxes. Then, voltage and current measurements were recorded using a data logger. To monitor thermal performance, K-type thermocouples were installed at three locations: on the rear surface of the PV panel, at the fluid inlet and outlet ports, and at strategic points within the thermal collector's flow channels. Crucially, the temperature reading from the outlet was used as the real-time input signal to the system controller to maintain the CCT mode. A silicon pyranometer was mounted in the plane of the array to simultaneously record incident solar irradiance. Data was collected at one-minute intervals from 08:00 to 18:00. The data logger was paired with the dEX 2.0 Logger software to monitor and retrieve temperature measurements, water flow intervals, voltage, and current data.

The experiment was conducted at the Solar Garden of Wisma R&D, University of Malaya Kuala Lumpur, from November 2022 to February 2023, during the rainy season of the Malaysian peninsula. Both panels were tilted at a 15° angle to the southern hemisphere to maximize irradiance exposure during the outdoor research (Mamun *et al.*, 2022). The outdoor experimental setup can be seen in Figure 2, with the primary PV and PVT equipment positioned near each other to allow for performance comparison.

The experiment was conducted on a sequential schedule. First, it compares PV versus PVT systems with the CF scheme,

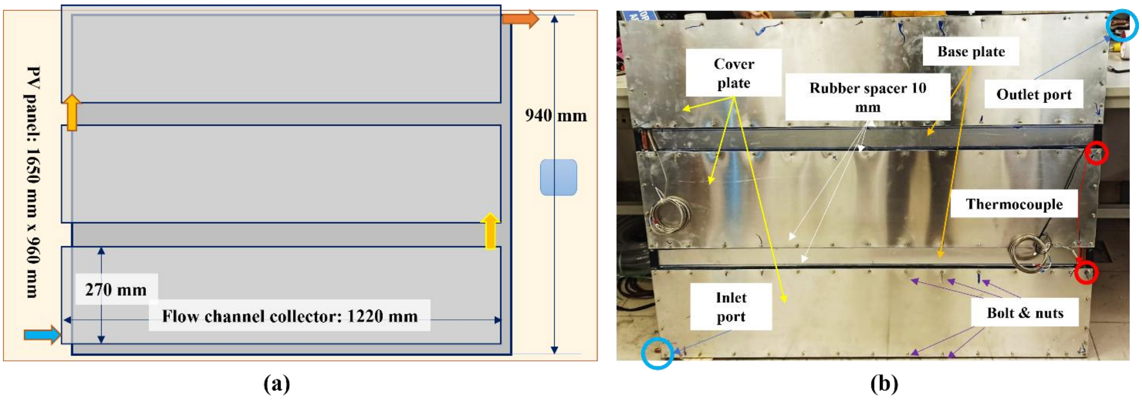

Fig 1. Sinusoidal flow channel thermal collector, (a) design drawing and dimension, and (b) assembled collector with thermocouple for temperature controller.

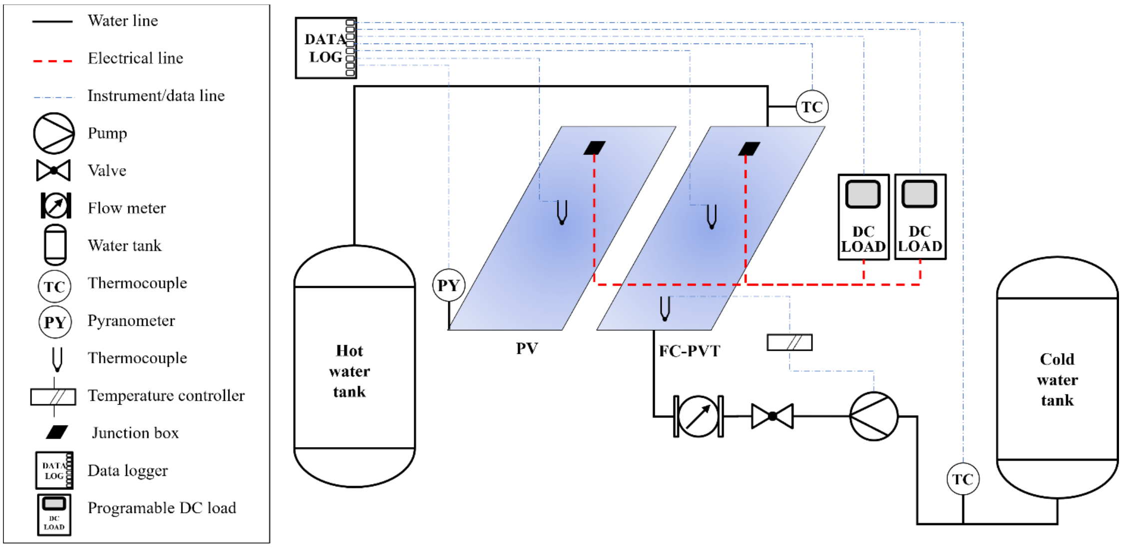

Fig 2. Schematic diagram of the experimental setup for outdoor experiment.

followed by PVT systems with the CCT scheme. In the initial experiment, cooling water was pumped from a cold-water tank and directed through the thermal collector before reaching the hot-water storage tank. The pump operation spanned from 08.00 to 18.00 daily, with the flow rate regulated using a ball valve installed before the flow meter. The water flow rate is adjusted within a 0.5 to 1.5 litre per minute (LPM) range in 0.25 LPM intervals. The complete data sets were obtained for various irradiance levels ranging from 100 to 750 W/m² at 50 W/m² intervals. Due to weather constraints, data collection for a specific combination of irradiance level and flow rate (referred to as one batch) may have taken more than one day until all irradiance fluctuations were covered. In contrast, the CCT scheme used an automated on-off controller to regulate pump operation based on temperature. A temperature sensor at the collector outlet triggered the pump to activate when the water reached 42 °C and deactivate when it cooled to 40 °C, maintaining the temperature within this hysteresis band. For this scheme, the water flow rate was maintained at a constant 2 LPM whenever the pump was active.

2.2 Energy analysis

The performance evaluation of a PVT system assesses the electricity generation, and heat collected from the thermal collector (Umam *et al.*, 2023). Two factors that influence the amount of solar energy absorbed are the surface area of the PV cells (A_c) and the irradiation level (G). In the CCT scheme, the solar energy (E_{in}) corresponds to the total irradiation received by PV cells in W/m²/day. The quantification of solar energy can be calculated using Equation (1) (Al-Waeli *et al.*, 2020).

$$E_{in} = A_c G \tag{1}$$

The electrical power from PV cells can be computed by multiplying the output voltage and current, as shown in Equation (2). In the CCT scheme, the electrical energy is calculated daily in watt hours (Wh). Equation (3) provides a measure of electrical efficiency, indicating the effectiveness of converting solar energy into electrical energy.

$$E_p = V * I \tag{2}$$

$$\eta_e = \frac{E_p}{E_{in}} \tag{3}$$

Furthermore, Equation (4) is used to calculate the thermal energy transported by the water based on mass flow rate ($\dot{m}$), specific heat capacity (Cp), and the temperature difference between the outlet and inlet water (Fayaz *et al.*, 2019).

$$E_t = \dot{m} C_{pf} (T_{out} - T_{in}) \tag{4}$$

The water flow rate is converted to a metric standard where $1\ \text{LPM} = 1.66667 * 10^{-5}\ \text{m}^3/\text{s}$. Then, the mass flow rate of water can be calculated using Equation (5). Afterward, the thermal efficiency can be determined using Equation (6).

$$\dot{m} = \rho \dot{V} \tag{5}$$

$$\eta_t = \frac{E_t}{E_{in}} \tag{6}$$

Table 1
The accuracy rate of the equipment used in the experiment

Instrument	Measurement	Range	Uncertainty
Programmable DC Electronic Load (Model: ET5410 Single-Channel)	Constant voltage	0.1 – 150 V	± 0.05%
	Current read-back	0 – 40 A	± 0.08%
	Power read-back	0 – 400 W	± 0.1%
Thermocouple (Model: K-type welded tip and rod)	Fluid inlet temperature	-270 – 1,372 °C	± 0.75%
	Fluid outlet temperature	-270 – 1,372 °C	± 0.75%
	Panel surface temperature	-270 – 1,372 °C	± 0.75%
Data logger (Model: DataTaker DT80)	Thermocouple DC voltage	0 – 30 VDC	± 0.1%
	DC Resistance	10Ω to 10KΩ	± 0.1%
Flow meter (Model: SHLLJ LZM-15)	Fluid flow velocity	0.5 – 4 LPM	± 4%
Pyranometer (Model: SP-12-L Apogee Silicon Pyranometer)	Solar irradiation	0 – 1,800 W/m²	± 2%

For CCT method, the thermal energy is only calculated when cold water is pumped into the thermal collector, and then the cumulative daily intake is determined, as shown in the equations (7) and (8) below.

$$E_{th} = \sum \dot{m} C_{pf} (T_{out} - T_{in}) \tag{7}$$

$$\eta_{th} = \left(\frac{E_{th}}{G_t * A_m * 3600} \right) * 100 \tag{8}$$

Finally, the overall efficiency of the PVT system is determined using Equation (9), which represents the ratio of the total energy output (electrical and thermal) to the solar energy.

$$\eta_0 = \eta_e + \eta_t = \frac{E_p + E_t}{E_{in}} \tag{9}$$

2.3 Uncertainty analysis

The uncertainty analysis is carried out to assess the measuring instruments and ensure the reliability and consistency of the experimental results. Table 1 presents the uncertainty percentages associated with the equipment from the manufacturers. The uncertainty evaluation should meet a 95% or higher confidence level to consider the results valid. The Equation (10) by Kline (1953) is used to calculate the overall equipment uncertainty in this study. The result of the uncertainty calculation for all instrumentation used in this experiment is ±4.45%.

$$eR = \left[\left(\frac{\partial R}{\partial V_1} e_1 \right)^2 + \left(\frac{\partial R}{\partial V_2} e_2 \right)^2 + \cdots \ldots + \left(\frac{\partial R}{\partial V_n} e_n \right)^2 \right]^{0.5} \tag{10}$$

3. Results and Discussion

3.1 Temperature profile

The performance evaluation of the PVT system includes an analysis of the surface temperature because an increase in the PV cell's temperature can reduce its electrical efficiency. Additionally, the applicability of the PVT system is dependent on the exit water temperature. Figure 3(a) shows the temperature profile of the PVT system during the outdoor test using CT schemes. In this scheme, the outlet water temperature fluctuates following variations in the PV panel temperature. Due to the continuous water flow cooling, the PVT surface temperature is kept lower than the PV panels. However, the CF method has practical difficulties since continuous pump operation utilizes additional electricity. Furthermore, the outflow water temperature may not reach the desired temperature, limiting its practical usefulness.

In contrast, Figure 3(b) illustrates the temperature profile of the PVT system using CCT schemes. The CCT method works by keeping the water temperature within a predetermined range of 40 °C. The pump is activated when the water temperature in the thermal collector hits 42 °C. The cold water is then introduced into the collector, displacing the hot water. The pump operation is engaged until the water temperature inside the collector falls below 40 °C, at which point the pump shuts down automatically. As a result, the CCT scheme ensures that the maximum surface temperature of the PVT panel remains generally constant at 50 °C.

Additionally, the sudden decrease in solar irradiance around 12:00 pm in Figure 3(a) is caused by shading from a building south of the research area. In November, during the first phase (using the CF method), the sun was closer to the southern hemisphere, causing the building to block sunlight around noon. In contrast, the sun moved closer to the equator during

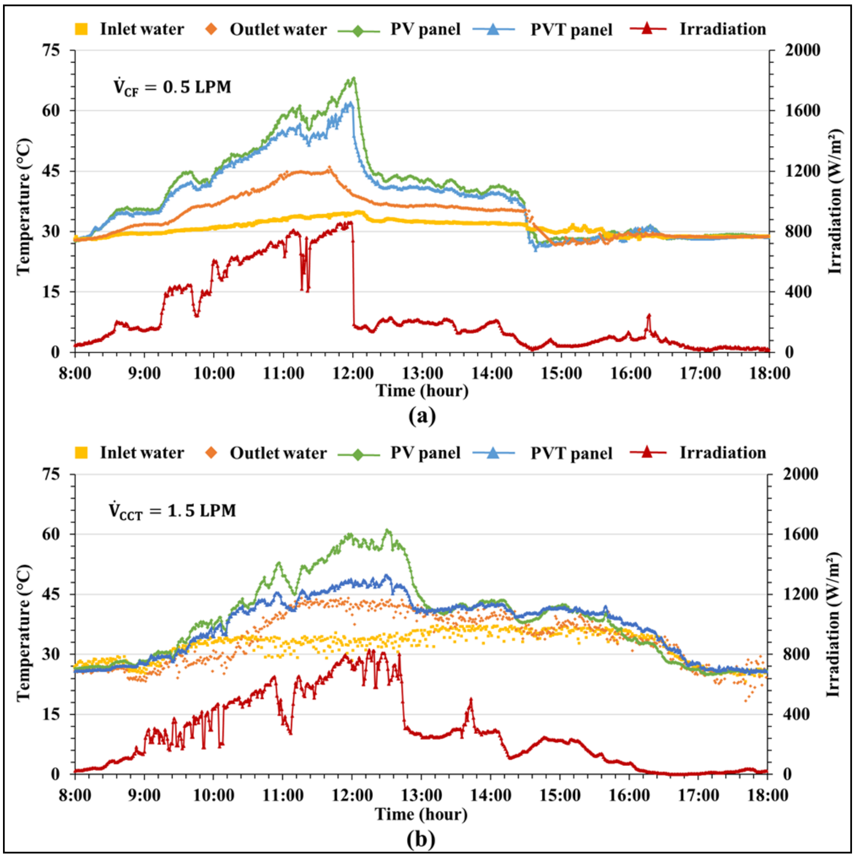

Fig 3. Temperature profiles of the PVT system under: (a) the CF scheme at 0.5 LPM on November 26, 2022, and (b) the CCT scheme on February 9, 2023.

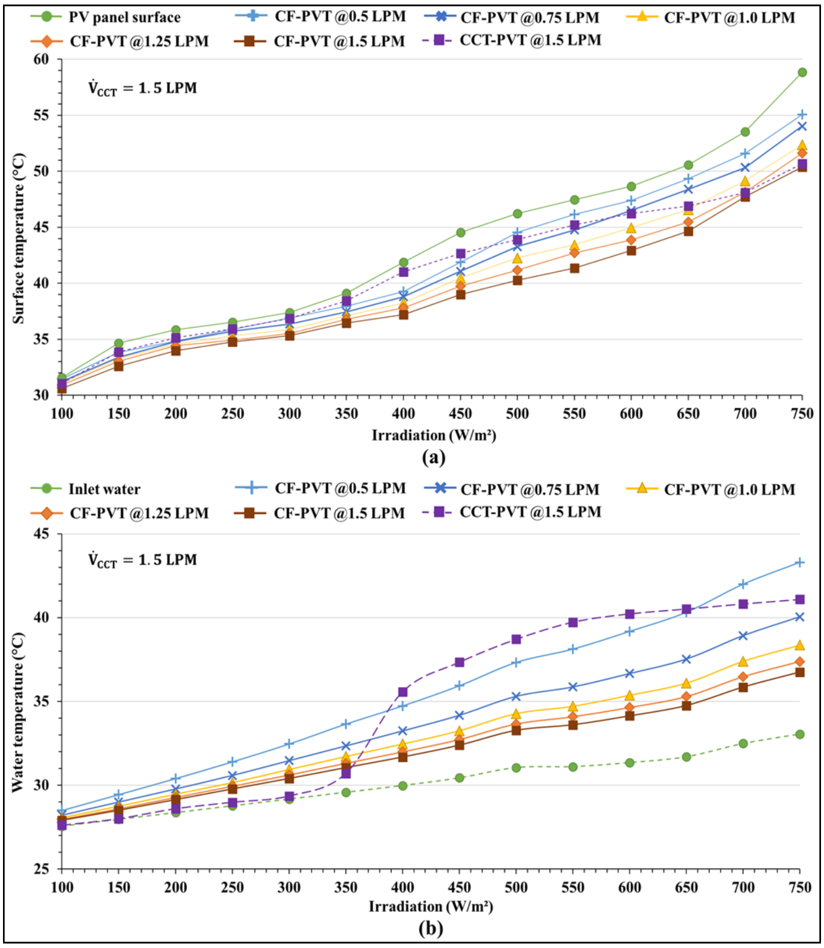

Fig 4. Effect of solar irradiance on the (a) surface temperature of PV/PVT panels and (b) outlet water temperature of the PVT system, under CF and CCT schemes.

the second phase (using the CCT method) in early February, as illustrated in Figure 3(b). This change resulted in shading beginning around 1:00 pm.

3.1.1 PV cells temperature

The PV cell temperature increased to 58.84 °C without sufficient cooling methods. Operating the PV cell below 85 °C is suggested for best performance and longevity, with a High-Temperature Destruct Limit of 120 °C to avoid high-temperature breakdown (Kern, 1999). Exceeding this threshold can significantly accelerate the degradation process of photovoltaic modules. As demonstrated in Figure 4(a), the PVT and PV panels in the CF scheme exhibit a steady rise in surface temperature as solar radiation intensifies. The PV surface temperature rises progressively from 31.59 °C at 100 W/ m² irradiation to 58.84 °C at 750 W/m² irradiation. The graph also demonstrates that the water flow rate affects cooling performance, with a larger flow rate resulting in more significant cooling of the PVT surface. At 750 W/m² irradiation, the surface temperatures of the PVT panel were 55.07 °C, 52.36 °C, and 50.39 °C for flow rates of 0.5 LPM, 1.0 LPM, and 1.5 LPM, respectively. These results indicate a maximum temperature drop of 8.45 °C when employing the CF scheme. This result is consistent with the modeling of a duct channel PVT system by Rahmanian & Hamzavi (2020). They found that the configuration exhibited a lower surface temperature of up to 8.28 °C compared to a harp collector with a flow rate of 0.83 LPM.

Compared to the CF method, the cooling performance of the PVT system using the CCT scheme shows negligible variation. In the morning, approximately 10.92 litres of cold water within the thermal collector acts as the thermal inhibitor, maintaining a lower surface temperature as the irradiation increases from 100 W/m² to 350 W/m². Subsequently, the PVT surface temperature gradually rises until the water temperature inside the collector reaches 42 °C, and the pump is activated automatically to circulate the water. This mechanism ensures that the temperature rise is contained to approximately 50 °C, maintaining a difference of about 10 °C above the water temperature in the collector.

Figure 5(a) depicts the average surface temperature of PV and PVT panels using the CCT scheme throughout the day as a proportion of total irradiation. The average solar irradiation for Peninsular Malaysia ranged from 3.91 to 4.30 kWh/m²/day (Hussin *et al.*, 2010). Even during periods of heavy solar irradiation, the PVT panel in the CCT scheme generally maintains a lower temperature than the PV panel. However, the PVT panel has a slightly higher average temperature in low-irradiation conditions where the water temperature does not meet the 42 °C threshold. Overall, the PVT panel exhibits an average surface temperature of 1.04 °C lower than the PV panel, with a maximum difference of 2.17 °C. However, this reduction is significantly smaller than that attained in the CF scheme and lower than the findings from previous studies. For instance, Salem Ahmed *et al.* (2019) observed an average temperature decrease in the flow channel PVT surface of 9.7 °C using the CF scheme at a flow rate of 0.45 LPM.

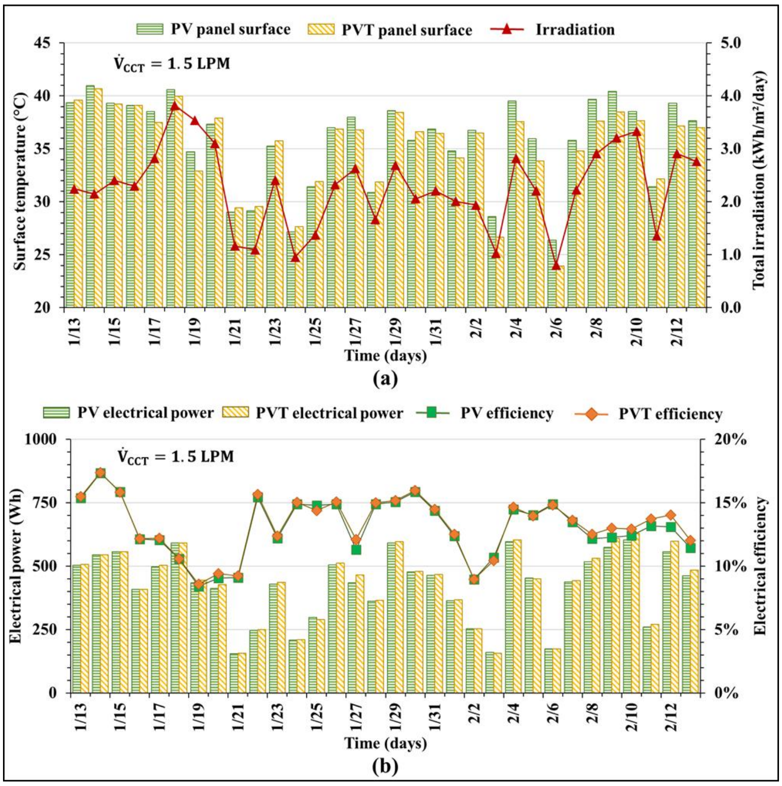

Fig 5. Daily performance of PV and PVT systems against daily solar irradiation under the CCT scheme; (a) average module temperature and (b) electrical power.

3.1.2 Output water temperature

The temperature changes in outflow water for testing PVT performance systems using the CF and CCT techniques are depicted in Figure 4(b). The outflow water temperature closely follows the PVT surface temperature in the CF scheme. The surface temperatures drop as the flow rate increases, resulting in lower water output temperatures. Maximum attainable water outlet temperatures at 750 W/ m² irradiation and flow rates of 0.5, 0.75, 1.0, 1.25, and 1.5 LPM are 43.30 °C, 40.05 °C,

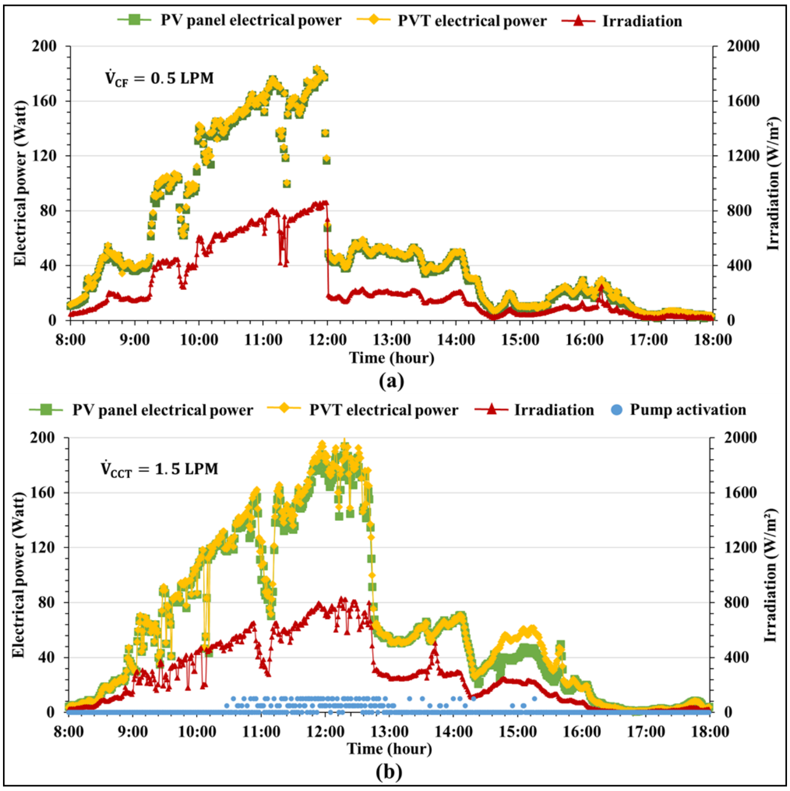

Fig 6. Comparative electrical performance of PV and PVT systems under s: (a) CF scheme at 0.5 LPM on November 26, 2022, and (b) CCT scheme at February 9, 2023

38.37 °C, 37.38 °C, and 36.75 °C, respectively. These results indicate lower outlet water temperatures compared to findings by Dubey & Tay (2013) in a similar weather environment. They found outlet water temperatures of 55.3 °C at a flow rate of 1.8 LPM and 52.1 °C at a flow rate of 3.6 LPM for FC-PVT. In addition, the CCT scheme attempts to maintain the outlet water temperature of PVT systems at 40 °C regardless of the radiation level. As a result, no hot water is produced during the low-radiation period. On a sunny day, the pump typically begins running at roughly 400 W/m² irradiation, triggered by the water temperature inside the thermal collector exceeding 42 °C. The pump ceases when the temperature falls below 40 °C, and the water heating process resumes. Higher radiation intensity increases the frequency of pump activation, resulting in more frequent water circulation.

3.2 Electrical performance

The electrical performance was evaluated using Equations (2) for electrical power and Equation (3) for electrical efficiency. Figure 6(a) illustrates the experimental results of the PVT system using the CF scheme and a flow rate of 0.5 LPM. It was discovered that the PV panel produces less power and has higher surface temperatures than the PVT system. The temperature and power profiles exhibit a close resemblance but with opposite outcomes compared to Figure 3(a). Despite achieving a significant temperature reduction, the power output increase remains relatively modest. Figure 6(b) depicts the PVT system experiment data employing the CCT scheme. The results demonstrate that the PVT panel using the CCT scheme generates more power than the CF scheme. In addition, Figure 6(b) captures the operational timing of the pump as depicted by the green dot in the CCT scheme. The lower position of the green dot corresponds to a 15-second operation, whereas the upper position corresponds to a 30-second function.

3.2.1 power generation

The experiment with the PVT system using the CF scheme shows a significant temperature reduction, especially at higher water flow rates. However, the finding indicates that the corresponding improvement in power generation is less substantial than expected. The comparison of the electric power output from PV and PVT systems employing CCT and CF schemes with varying flow rates is illustrated in Figure 7(a). In the CF scheme, where maximum cooling is achieved at a 1.5 LPM flow rate, the highest power enhancement by the PVT system is 5.6%. The PVT panel generates 145.51 watts of power, in contrast to the PV power output of 137.80 W at 600 W/m² irradiation. This finding is similar to the results of an experiment with the FC-PVT system at a constant flow rate of 1.2 LPM reported by Bashir *et al.* (2018). They found that the maximum increase in power was approximately 5 watts, although the PVT temperature was 7.2% lower than the PV panel.

3.2.2 Electrical efficiency

The variations in electrical efficiency for PV and PVT panels using the CF scheme are illustrated in Figure 8. With an

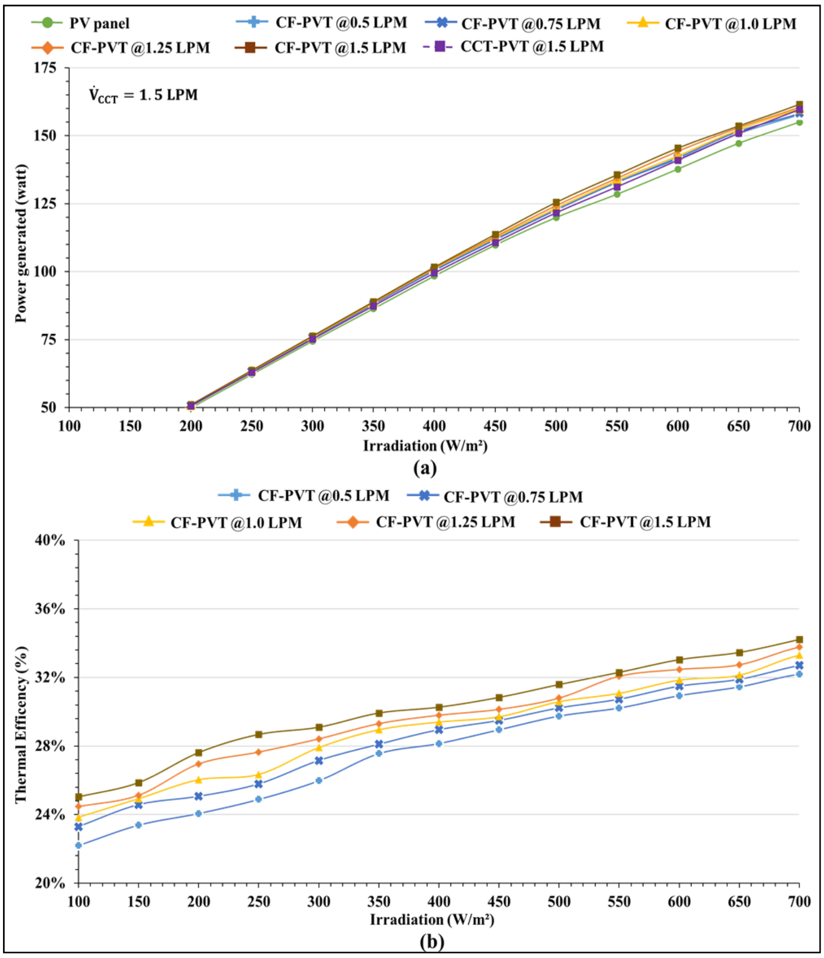

Fig 7. Effect of solar irradiance on (a) the power output of PV and PVT systems under CF and CCT schemes, and (b) the thermal efficiency of the PVT system under the CF scheme at various flow rates.

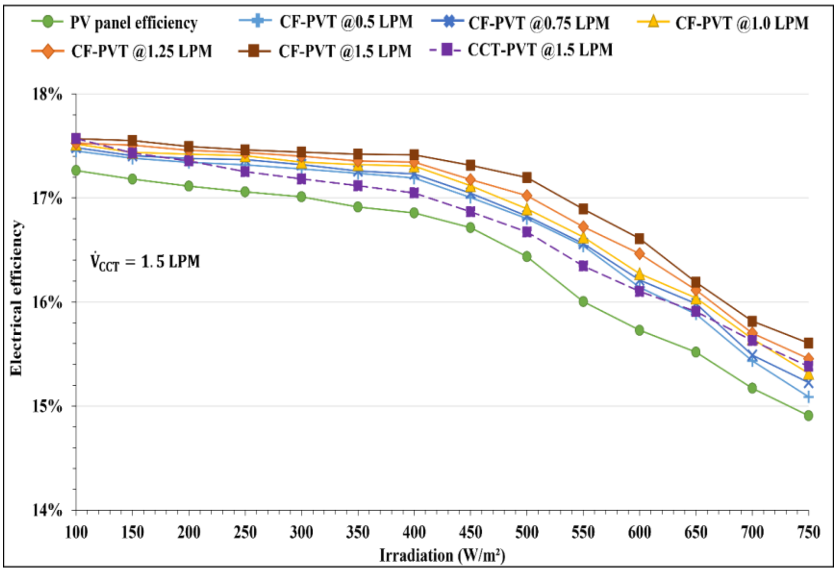

Fig 8. The effect of irradiance on PVT electrical efficiency in CF and CCT schemes.

irradiance of 100 W/m² and a relatively low temperature of 31.59 °C in the morning, the PV panel generates 25.21 watts of electricity with an efficiency of 17.26%. Conversely, as the temperature rises to 58.84 °C at 720 W/m² irradiation, the PV panel's power output increases to 163.25 watts, but its electrical efficiency drops to 14.91%. To quantify the temperature and efficiency relationship, experimental data from this study shows that the electrical efficiency of the PV cells declines by approximately 0.18% for every 1 °C rise in temperature. This rate of decline is lower than the temperature coefficient for crystalline silicon cells found by Dubey & Tay (2013), which ranges from 0.4% to 0.5% per °C. For example, under an irradiance of 850 W/m² and a panel temperature of 64.43 °C, the predicted efficiency loss using the model is 2.84%, closely aligning with the observed experimental reduction of 2.88%.

Furthermore, with a flow rate of 1.5 LPM, the efficiency of the PVT system is 0.89% higher than that of a PV panel, corresponding to a power output of 128.53 watts versus 135.67 watts at 550 W/m² irradiation. These findings are consistent with those of Dubey & Tay (2013), who observed a 0.4% average increase in electrical efficiency for FC-PVT modules with a water flow rate of 3.6 LPM.

In contrast, the experiment with the PVT system using the CCT scheme obtained slightly different results, albeit significant enhancements. Figure 5(b) illustrates the electrical power and efficiency data of the PV and PVT systems under the CCT scheme from outdoor experiments conducted between January and February 2023. Throughout the observation period, the average PV electrical efficiency was 13.04%, while that of PVT was 13.23%. Compared to the CF scheme, the average electrical efficiency of the PVT system is slightly lower at smaller irradiance levels. This difference can be attributed to the intermittent cooling process employed by the CCT scheme. However, the electrical efficiency of the PVT system improved as irradiance levels increased. Compared to conventional PV panels, the average increase in electrical efficiency is 0.26%, and the maximum gain is 0.96%.

Furthermore, the daily power generated by the PVT system using the CCT scheme is similar to the CF scheme. The average power improvement by the PVT system in the CCT scheme is 2.11%, with a maximum of 7.32%. These results are consistent with the outcomes of prior investigations by Nahar *et al.* (2017) concerning the FC-PVT system. Their numerical and experimental studies observed a 0.15% and 0.13% enhancement in PVT electrical efficiency compared to a PV panel, respectively.

3.3 Thermal performance

The thermal performance was analyzed using Equations (4) for thermal energy gain and equation (6) for thermal efficiency. For the CCT scheme, daily cumulative thermal energy and efficiency were calculated using Equation (7) and (8), which form the basis of the results discussed in this section. The thermal efficiency of the PVT system across different irradiations in the CF scheme is presented in Figure 7(b). The PVT system exhibits a maximum thermal efficiency of 35.05% at 750 W/m² irradiation and a 1.5 LPM flow rate. Other flow rates yielded comparable results, with a consistent trend of decreasing thermal efficiency as the flow rate decreased. The PVT thermal efficiency using the CF scheme with a flow rate of 0.5 LPM was 32.38%. These findings are relatively low compared to previous PVT research using similar thermal collector designs. For instance, Ji *et al.* (2006) found a PV cell temperature of 48.49 °C and a thermal efficiency of 45.57% at an irradiation of 423.27 W/m² in their mathematical model of a PVT system using a box channel collector. However, Dubey & Tay (2013) found similar results: the maximum thermal efficiency of FC-PVT is 39.4%. Also, Rahmanian & Hamzavi (2020) found an average thermal efficiency of 63.87% at a 0.25 LPM flow rate and 30 °C inlet temperature in the experiments of PVT using duct channels.

In contrast, the evaluation of PVT thermal performance in the CCT scheme calculates the daily thermal energy as the sum of the thermal energy obtained during each pump operation. The thermal efficiency is then calculated by dividing the daily thermal energy by the daily total solar energy received on the PVT surface. Figure 9(a) depicts the thermal energy obtained after adjusting the PVT system's thermal efficiency and total efficiency. During the data collection period, there were seven days of pretty low irradiance, so the pumps did not operate and no thermal energy was collected. The maximum daily thermal energy obtained by a PVT system employing the CCT method is 2.98 MJ, with a maximum thermal efficiency of 17.89%. Thus, by adding the electrical

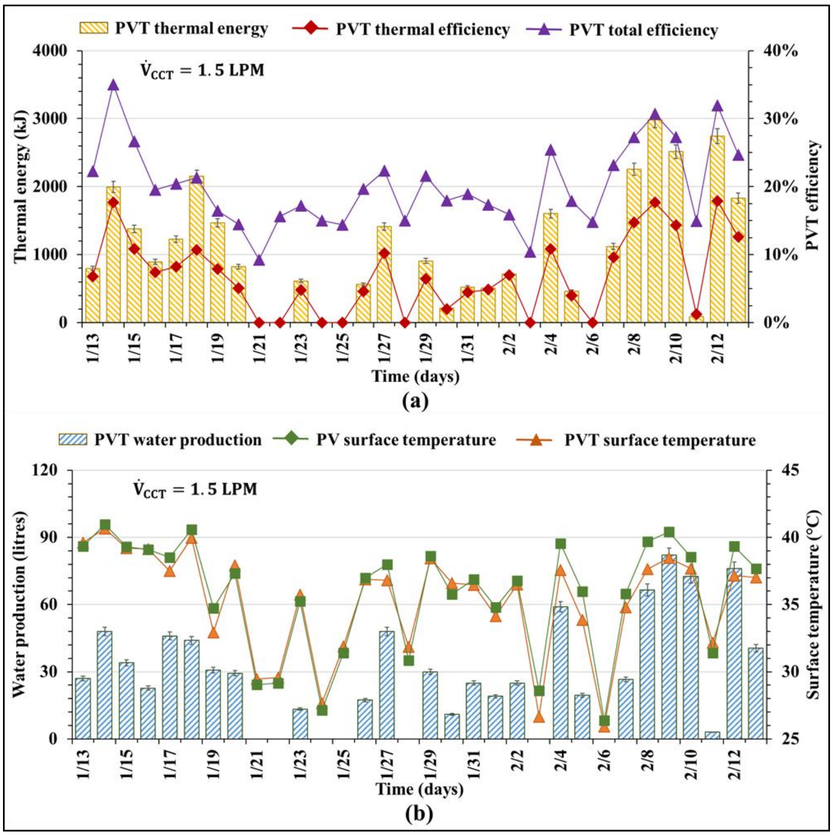

Fig 9. Daily thermal output of the PVT system operating under the CCT scheme, showing (a) useful thermal energy gain and (b) volumetric hot water production.

efficiency, the maximum overall efficiency of the PVT system in this scheme reached 35.03%. These findings indicate that PVT systems operate more effectively at high irradiance when employing the CCT scheme, as it optimally converts solar energy into electricity and heat while imposing a minimal load on water circulation.

Furthermore, evaluating PVT system performance using the CCT scheme requires a more thorough metric than the temperature difference between inlet and outlet water. Daily thermal productivity is a more accurate parameter to assess the effectiveness of PVT systems under CCT schemes. Figure 9(b) shows the daily hot water production of the PVT system using the CCT scheme, showing variability based on weather conditions with a maximum of 82 litres per day. The relationship between water production, PVT temperature, and electrical efficiency indicates that significant water production leads to a lower PVT temperature and higher electrical efficiency than PV panels. Additionally, the power for pumping is also a crucial factor in assessing the overall performance of the PVT system, as it utilizes power produced by PVT panels.

This experiment employed a 100-watt pump for water circulation. On average, 0.032 kWh of pump energy was needed to produce one kilojoule of hot water from the PVT system. For instance, on the sunniest day, the system produced 2.98 MJ of thermal energy. If operated under a CF regime, the pump might consume up to 0.8 kWh per day, assuming 8 hours of continuous use. In contrast, the CCT scheme reduced pump energy consumption to approximately 0.095 kWh, yielding an estimated 88% reduction in electricity use.

The operation of the PVT system using the CCT method has several advantages over the CF scheme. First, it optimizes the energy consumption of pumps by activating them only when necessary, thereby reducing energy waste. Second, it ensures water is collected at a constant temperature, enhancing the system's overall performance. Third, it continues to improve electrical power and efficiency. In addition, its thermal performance is enhanced, particularly under intense irradiation. However, during periods of low solar radiation, the PVT system may produce little or no hot water, and the cooling effect is also minimal.

4. Conclusion

The optimal maintenance of output water temperature is crucial for utilizing PVT systems in real-world applications. This study compares PVT systems using CF and CCT schemes regarding surface temperature reduction, electrical power, and thermal productivity. The findings indicate that PVT systems using the CCT scheme offer comparable power improvements to the CF scheme while minimizing power usage for pumping. The CF scheme achieved a maximum thermal efficiency of 35.05% at 750 W/m² and 1.5 LPM, with a peak electrical power enhancement of 5.6% over standalone PV panels. However, it requires continuous pump operation, leading to higher auxiliary energy consumption and variable outlet water temperatures. In contrast, the CCT scheme maintained a stable outlet temperature of 40 °C regardless of irradiance fluctuations, delivering a maximum daily thermal energy of 2.98 MJ and an overall efficiency of 80.94%. Despite a slightly lower electrical gain with an average of 3.17%, the CCT system achieved an estimated 88% reduction in pump energy use compared to CF operation, showing its better energy management.

The utilization of the CCT scheme in the PVT system ensures a consistent and reliable outlet water temperature without requiring user intervention or flow rate adjustment. While the CF scheme in the PVT system provides superior cooling, the

CCT scheme provides more promising thermal productivity. Further research and optimization efforts are needed to improve the thermal output and electrical efficiency of PVT systems under various operating conditions. It is also necessary to investigate how water flow rate affects PVT performance in the context of using CCT schemes.

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