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To cite this version:

Mustapha Salihi, Maryam El Fiti, Yasser Harmen, Younes Chhiti, Ahmed Chebak, et al.. Efficiency enhancement of photovoltaic module using bio-based eutectic phase change material: An experimental study. E3S Web of Conferences, 2024, E3S Web of Conferences, 545, pp.02001. 10.1051/e3sconf/202454502001 . hal-04687117

HAL Id: hal-04687117

https://hal.univ-lille.fr/hal-04687117v1

Submitted on 4 Sep 2024

Efficiency enhancement of photovoltaic module using bio-based eutectic phase change material: An experimental study

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Abstract. Photovoltaic cells convert absorbed solar energy into electricity by transforming the incident visible wavelengths of solar radiation on their surface, while the other wavelengths are transformed into thermal energy. However, the main issue they face is the elevated temperature of PV modules during operation, which reduces their energy production efficiency. Thermal control of photovoltaic panels using phase change materials (PCMs) has been a potential solution to overcome this problem and perform as a passive cooling material. In this study, the effectiveness of using a novel bio-based eutectic PCM in thermal regulation and efficiency enhancement of the PV panel was studied experimentally. The prepared PCM was characterized and then integrated onto the backside of the PV module. An indoor experimental study was conducted to compare the performance of PV-PCM with a reference PV panel without PCM. The DSC results revealed that the prepared PCM has an appropriate phase change temperature and latent heat capacity for cooling a PV module. In addition, the incorporation of PCM on the backside of the PV panel (PV-PCM) resulted in a significant reduction in surface temperature by 11.46 °C (14.45 %) compared to the reference PV (PV-ref) panel without PCM. Notably, an increase of 7.23 % in the maximum output power is observed in the PV-PCM system.

1 Introduction

The global energy demand has been a pressing issue in recent years. As the global population continues to grow and economies develop, the demand for energy is increasing at an alarming rate [1]. This growing demand poses a significant challenge, not only in terms of meeting energy needs but also in addressing the associated environmental concerns. The traditional reliance on fossil fuels, such as coal, oil, and natural gas, has proven to be unsustainable and detrimental to the environment. These sources of energy contribute significantly to greenhouse gas emissions, trapping heat in the atmosphere and leading to global warming

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[2]. The consequences of climate change are already being felt around the world, with more extreme weather events, rising sea levels, and disruptions to ecosystems. The transition to renewable energy sources is crucial to address these pressing issues. Solar energy, in particular, stands out as a promising solution. Solar energy is environmentally friendly and freely available in all parts of the world [3]. Through the use of photovoltaics (PV), electricity can be directly generated from solar energy, without the need for any heat engine devices.

The photovoltaic (PV) efficiency, which refers to the ability of a solar cell to convert sunlight into electricity, depends primarily on solar radiation intensity, the properties of the semiconductor materials used in the cells, and the operating temperature [4]. Commercially available PV panels generally have efficiencies ranging from around 15% to 20% [5]. This means that only 15-20% of the solar irradiance is converted into electricity, while the remaining energy is typically dissipated as heat. However, the heating of PV cells decreases their efficiency and reduces the lifespan of PV panels. In the case of crystalline silicon cells, elevated temperatures can cause a decrease in productivity by approximately 0.4 to 0.65% for every degree increase in temperature [6]. Thus, it is recommended to implement thermal management techniques for PV modules in order to ensure efficient electricity production.

Recently, there has been significant research on various active and passive techniques to address the issue of PV heating. Active cooling systems employ devices such as fans, blowers, or pumps to manage the temperature, while passive cooling systems do not require external power to operate. Passive cooling holds several advantages over active cooling, including lower costs, easier installation, and no energy consumption. For example, S. Nižetić et al. [7] conducted an experimental study on the cooling of PV panels by spraying water on both sides of the panel. The results reported an improvement of 5.9% in efficiency and 7.7% in electrical power when managing a PV panel at 24 °C. Another study by E. Wilson [8] investigated the effect of water flow on the backside of a PV panel and achieved an enhancement of 12.8% in PV efficiency and a reduction of PV surface temperature by 32 °C. In addition, Maghrabie et al. [9] conducted an experimental study focusing on the implementation of an air-cooling system to enhance the performance of PV cells. The results revealed that the surface temperature of the PV cells decreased by approximately 10 % on the front side and 11 % on the back side when using the air-cooling system. A. Amelia et al. [10] developed an active cooling system based on forced convection induced by fans attached to the back side of PV panel. The results demonstrated that the average PV panel temperature was reduced by about 22.22 %.

One of the most effective passive cooling techniques for standalone photovoltaic (PV) systems is the utilization of Phase Change Materials (PCMs). PCMs are materials that have the ability to store and release a significant amount of energy during phase transitions as a latent heat [11]. These materials have numerous applications, including the enhancement of thermal comfort in buildings [12], battery thermal management [13], industrial waste heat recovery [14], [15], and electronics cooling [16] etc. Several studies have been conducted to mitigate the overheating of PV panels by using PCMs. S.A. Nada and D.H. El-Nagar [17] used paraffin (RT-55) as a PCM to reduce the PV panel temperature and increase its efficiency. A gain of 7.1% in average efficiency was observed. The effect of incorporation of PEG 1500 as PCM into PV panel was analysed by S.S. Bhakre et al. [3]. The results showed that use PCM decreases PV panel temperature by 10.59 %. In addition, H.M. Maghrabie et al. [18] conducted an experimental investigation to assess the impact of PCM thickness on reducing the temperature of PV panel using paraffin RT-42 as PCM. The results revealed that the utilization of a 3 cm thick PCM led to a 14.4% increase in PV electrical efficiency. In a study performed by M. Lotfi et al. [19], the combined effect of using PCM and reflector on the performance of photovoltaic modules was investigated. This study achieved a 12.5% enhancement in electrical output. Moreover, Q. Li et al. [20] developed a numerical model that incorporated PCM and fractal fins for the thermal management of PV cells. They found that the adoption of fractal fins could reduce the front plate temperature and improve its homogeneity over a given operating time.

Based on the literature reviewed, it is evident that there is a need to expand the existing database of practical performance for PV systems incorporating PCM. The selection of PCM plays a critical role in designing effective cooling systems for PV applications. In this study, a novel bio-based eutectic PCM with suitable phase change temperature and latent heat of fusion was prepared by combining two organic fatty acids: lauric acid and oleic acid. Bio-based PCMs offer several advantages over traditional paraffin PCMs, including lower flammability, reduced costs, environmental friendliness, and have a reduced carbon footprint. Therefore, the objective of the present study is to design an experimental setup to evaluate the impact of incorporating the newly developed bio-based PCM within the PV panel. The study aims to investigate the effects of PCM integration on both the thermal and electrical performance of the PV panel, as well as its ability to effectively regulate the panel temperature. Detailed measurements of temperature distributions, open-circuit voltage, short-circuit current, I-V curves, and output power were recorded and analysed for both the reference PV panel and the PV-PCM panel.

2 Methodology

2.1 Experimental setup

The real representation of the indoor experimental set-up and the schematic diagram are illustrated in Fig. 1 and Fig. 2, respectively. The experimental setup was constructed at the GTI-faculty laboratory. It consists of two identical polycrystalline silicon PV panels with a nominal power capacity of 12 W and dimensions of 430x350x17 mm. One panel, denoted as PV-ref, serves as the reference panel without PCM integration. The other panel, denoted as PV-PCM, incorporates the prepared eutectic PCM. To set the inclination angle of the PV systems at 30° relative to the horizontal axis, an adjustable metal stand with a clinometer was used. The experimental setup also includes a halogen lamp (Philips, 1000 W) as a sun simulator. According to the literature [21], tungsten halogen lamps have been widely used as sun simulator. To measure the temperature temporal variation of front surface, five K-type thermocouples with an accuracy of ±0.5 °C are attached to each PV panel. These thermocouples are calibrated using a mercury thermometer and then connected to a data logger type MADGETECH (TCTemp X-Series), which has an accuracy of ± 0.01 °C, to record the data at intervals of 1 minute. The positions of the thermocouples are demonstrated in Fig. 1 (a).

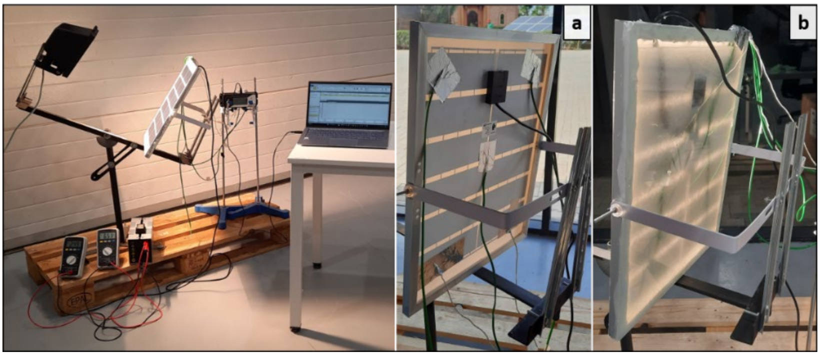

Fig. 1. Real representation of the experimental setup with thermocouple location: a) PV-ref, b) PV-PCM.

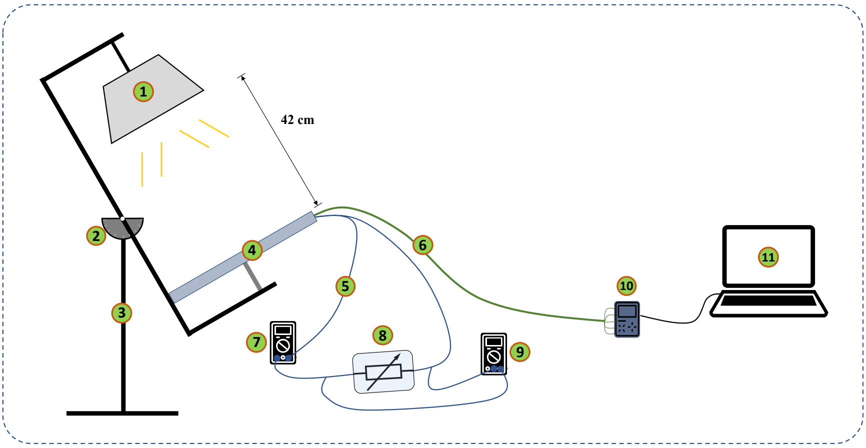

Fig. 2. Schematic diagram of the experimental setup: 1) Sun simulator, 2) Clinometer, 3) Metal stand, 4) PV panel, 5) Connectors, 6) Thermocouples, 7) Ammeter, 8) Rheostat, 9) Voltmeter, 10) Acquisition system, 11) Laptop.

In addition, digital multimeters (Multimetrix, DMM.111) and a variable resistance (rheostat type JEULIN, 100 Ω, 160 W) were used to measure the electrical parameters of the solar PV panels. The measurements were taken simultaneously with and without load (rheostat) to draw the respective I-V characteristic curves. Sun simulator irradiance was measured using a PV reference cell (NES Solar Irradiation Sensor SOZ-03 [22]), which has an error rate of less than ±3%.In order to obtain 1000 W/m², the distance between the PV panel and the lamp must be 42 cm.

2.2 PCM preparation

In this study, a PCM eutectic mixture was formed by combining lauric acid and oleic acid in an 80:20 ratio. Lauric acid (PCT of 44-46 °C) and oleic acid (PCT of 13-14 °C) are bio-based PCMs obtained from 'VWR Chemicals' and 'Sigma Aldrich', respectively. The prepared combination was then agitated at a speed of 500 rpm for 4 hours under 60 °C to ensure a homogeneous mixture (see Fig. 3). A glass plate with a thickness of 4 mm (with the same length and width of the PV panel) is directly attached to the backside of the PV panel using silicone adhesive. A 1.7 kg of the prepared eutectic PCM is then poured between the PV panel and the glass plate, as shown in Fig. 3.

Fig. 3. PV panel system set up: covering the backside of the panel and filling the system with the melted PCM.

The melting and solidification temperatures, as well as the latent heat of the prepared PCM were determined by using the differential scanning calorimetric (DSC) type DSC Q100. According to the DSC results at a constant heating/cooling rate of 5 °C/min (see Fig. 4), the melting and solidification temperatures of the prepared PCM are 41.03 °C and 32.37 °C, respectively. Besides, the latent heat of fusion is 152.7 kJ/kg, while the latent heat of solidification is 162.6 kJ/kg. The phase change temperature of the resulting PCM was found to be suitable for heat extraction from PV modules. The appropriate PCM melting temperature for PV cooling in the hot climates depends on several factors, including the specific location, the average daily temperature, and the intensity of solar radiation [23]. However, in general, a PCM melting temperature between 34 °C and 46 °C is recommended for the hot and dry climatic conditions [24]. This range ensures that the PCM can absorb heat from the PV modules during the hottest part of the day, when the ambient temperature is highest.

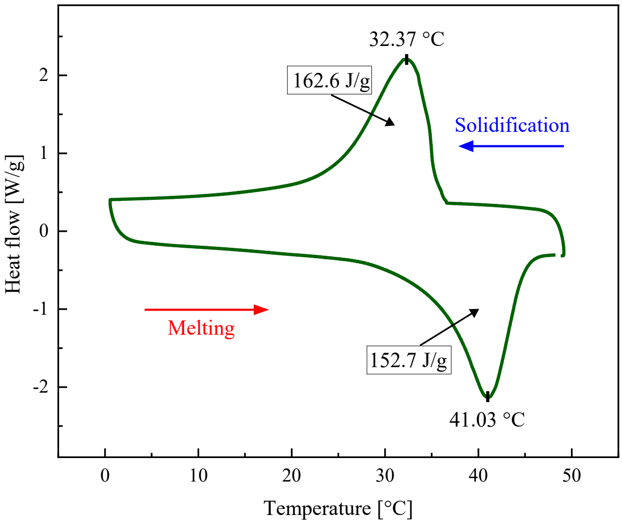

Fig. 4. DSC heating/cooling curves for the eutectic PCM.

2.3 Data reduction and performance parameters

To evaluate the performance of both PV systems, a set of indicators was calculated during the experimental procedure. The incident solar radiation on the front surface of a PV module is calculated by:

$$P_{inc} = G.A \tag{1}$$

Where A is the PV panel area [m²], and G is the incident solar radiation intensity [W/m²].

Also, the maximum obtained power of PV module is computed using the following formula:

$$P_{max} = V_{max}.I_{max} \tag{2}$$

V_{max} and I_{max} are module maximum values of voltage [V] and current [A], respectively. In addition, the electrical efficiency of a PV module is calculated by the following equation:

$$\eta = \frac{V_{max}.I_{max}}{G.A} = \frac{P_{max}}{P_{inc}} \tag{3}$$

The fill factor FF is defined as the ratio between the maximum power generation of a PV module and the multiplication of the open-circuit voltage V_{oc} and the short-circuit current I_{sc}, as follows:

$$FF = \frac{V_{max} \cdot I_{max}}{V_{oc} \cdot I_{sc}} \tag{4}$$

3 Results and discussion

3.1 PV temperature regulations

The primary objective of this study is to establish a reliable cooling system for the PV panel. To achieve this, it is crucial to determine the temperature distribution of the panel. Two experiments were conducted under identical conditions. In the first experiment, the PV panel without PCM was exposed to lamp radiation (1000 W/m²) for a duration of 3 hours. In the second experiment, the PV panel with PCM attached to its backside was also subjected to the same radiation and duration. The ambient temperature during the experiments ranged between 30.21 °C and 31.14 °C. It is important to note that these experiments were conducted at night to eliminate any radiation effects on the PV panel, except for the sun simulator.

Fig. 5 presents the average temperature of the backside of the PV panel for both cases with and without PCM. As can be seen in this figure, the average temperature profile of the PV panel without PCM increases sharply at the start of the experiment and reaches to the steady temperature after 38 min when the heat input to the PV cell, caused by irradiation, equals the heat loss from the PV panel to the surrounding environment through convection. At this stage, the PV panel reaches a maximum temperature of 79.27 °C, which can be attributed to the conversion of excess photon energy into heat instead of electrical energy. However, when the PCM is attached, the PV panel temperature is reduced to 67.81 °C under the same conditions. The temperature profile of the PV panel with PCM exhibits a different response. As observed, the temperature initially increases at a slower rate compared to the PV panel without PCM. It then reaches a constant temperature corresponding to the PCM melting point. Afterward, the temperature increases again, eventually reaching the maximum value and stabilizing after 120 minutes. The average temperature reduction (ΔT) of PV panels using the eutectic PCM is 11.46 °C, which correspond to 14.45 % reductions in the PV temperature.

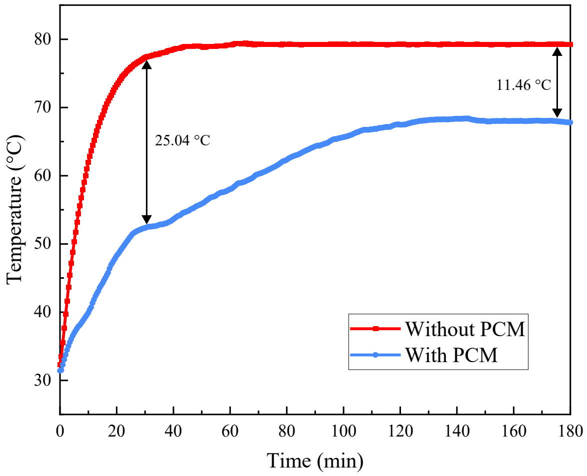

Fig. 5. Comparison of average temperatures for the PV panel backside with and without PCM.

To effectively assess the PCM's impact on PV panel temperature reduction, the temperature measurements from five thermocouples positioned at the backside of the PV panel are depicted in the Fig. 6. The figure clearly demonstrates the temperature distribution along the panel surface, revealing noticeable differences. The highest temperature distribution is observed at the upper part of the PV panel (T1 and T2), while the lower part exhibits the lowest temperature distribution (T4 and T5). This temperature variation can be attributed to the behaviour of the PCM during melting. The liquid and solid PCM have different densities, causing the liquid to flow towards the upper region and heat the solid PCM at the upper part. This creates natural convection and accelerate the PCM melting process in the upper region.

Consequently, the PCM effectively demonstrated its capability for thermal management of PV panels under hot environmental conditions. The PCM can absorb heat from the panel during the daytime when it is exposed to sunlight, undergoing a phase change from solid to liquid. During the night-time or periods of lower solar radiation when the PV panel is not generating as much heat, the PCM releases the stored heat by solidifying. This transition causes the PCM to change from a liquid state to a solid state, preparing it for the next cycle. The released heat helps to regulate the temperature of the PV panel, preventing it from overheating and maintaining optimal operating conditions.

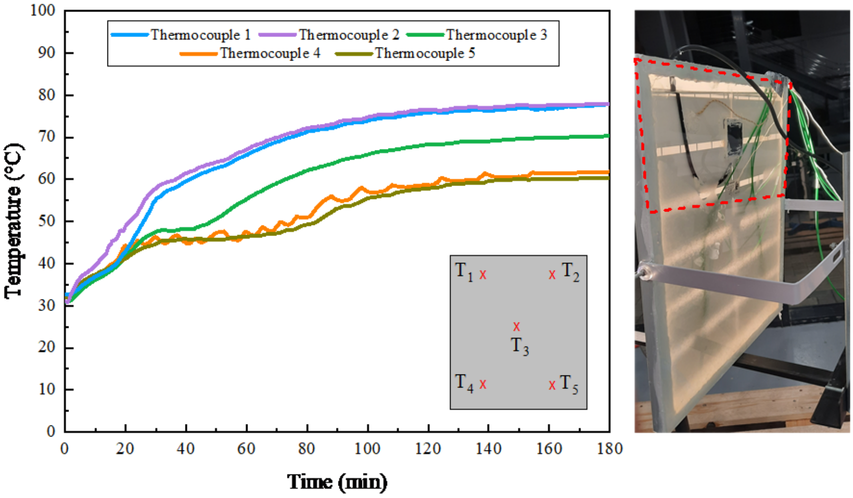

Fig. 6. Temperature measurements for the PV panel with PCM.

3.2 I-V curve

At each measurement point of the reference PV-ref and PV-PCM, the I-V curve data were obtained by varying the variable resistance. The measurement process started with the open circuit condition (maximum load) to determine the V_{oc}. Then, the resistance was gradually decreased, and the corresponding current (I) and voltage (V) values were recorded until reaching zero resistance (short-circuit conditions) to obtain I_{SC}. The I-V characteristic was plotted for each measurement of the two PV modules. An example of the I-V curve is provided in Fig. 7 at four different time intervals (1 min, 30 min, 60 min, and 120 min). A detailed description of the open circuit voltage and short-circuit current measurements for the reference PV panel and PV-PCM panel throughout the duration of the experiment is provided in the following sections.

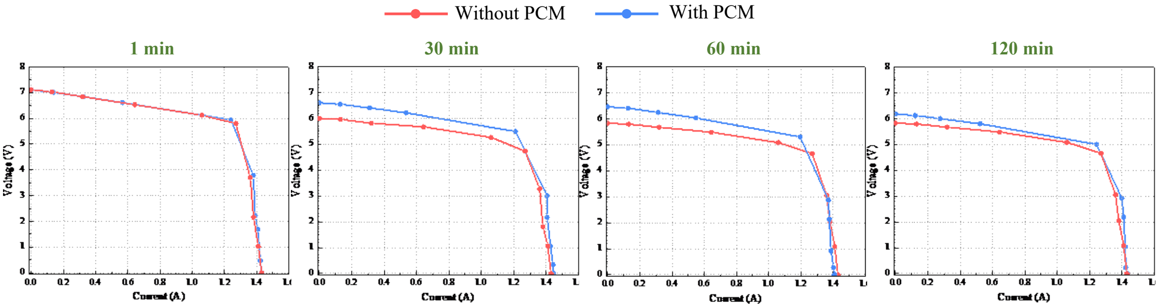

Fig. 7. I-V curve of the PV-ref and PV-PCM at four different time intervals.

3.3 Open-circuit voltage & short-circuit current

Fig. 8 represents the variation of open-circuit voltage (V_{oc}) and short-circuit current (I_{SC}) for the reference PV module and the PV-PCM module. As shown in the figure, in the case without PCM, V_{oc} experiences a sharp drop before 30 minutes and then stabilizes at 5.91 V. On the other hand, in the case of the PV module with PCM, the V_{oc} experiences a slight drop and remains stable for a longer duration at 6.4-6.7 V. Subsequently, the V_{oc} stabilizes at 6.23 V, which corresponds to a 5.41% increase attributed to the use of the PCM. This behaviour demonstrates an inverse relationship with the temperature profiles presented in Fig. 5. As discussed earlier, the cooling effect of the PCM on the PV panel improves the voltage performance since V_{oc} is highly influenced by temperature. Even after three hours, a difference of 0.32 V between the PV-ref and the PV-PCM is still noticeable. The variation of I_{SC} over time during the experiment is shown in Fig.8 (b). The figure illustrates that both the reference PV module and PV-PCM module exhibit similar I_{SC} values at the beginning of the experiment. However, a slight increase in I_{SC} is observed for the PV panel without PCM as the temperature increases. This can be attributed to the slight impact of temperature on the current. It can be concluded that integrating PV modules with PCM has negligible influence on I_{SC}, which primarily varies in response to changes in incident solar radiation intensity.

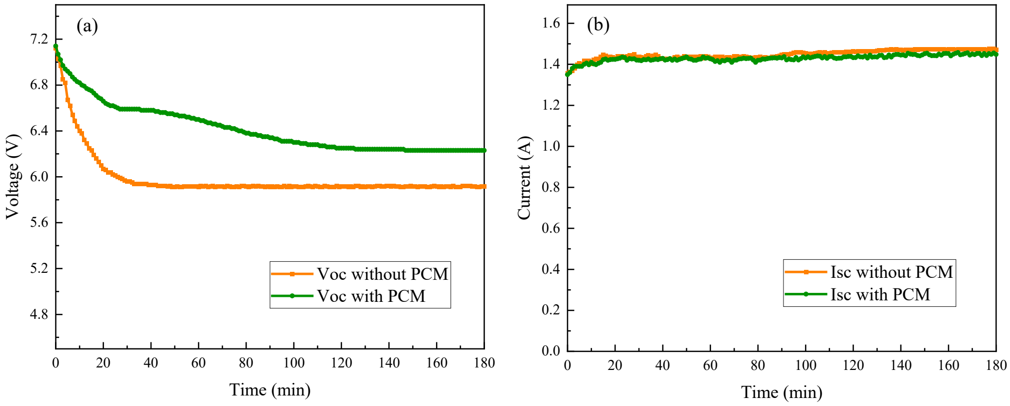

Fig. 8. Variation of (a) V_{oc} and (b) I_{sc} for reference PV module and PV-PCM module.

3.4 Maximum output power

To evaluate the impact of incorporating PCM in the direct current (DC) output power of PV panel, the maximum output power is calculated using Equation (2). Additionally, to quantify the performance enhancement of the PV-PCM module in comparison to the reference PV without PCM, the power enhancement ratio is calculated as defined in Equation (5):

$$\text{Power enhancement ratio } = \frac{Maximum\ power_{PV-PCM} - Maximum\ power_{PV-ref}}{Maximum\ power_{PV-PCM}} \tag{5}$$

Fig. 9 shows the variation of maximum output power and power enhancement ratio as time progressed. It was clear that the PV module output power was affected by the binary eutectic PCM. Initially, the maximum output power follows the same pattern until 10 minutes, resulting in a zero-power enhancement ratio. After that, the power enhancement ratio started to rise and reaches a maximum of 10 % at 15 min. At this time, the output power for the PV-ref panel is 6.12 W, while the corresponding value for the PV-PCM panel is 6.81 W. These findings can be attributed to the temperature reductions depicted in Fig. 5, as discussed earlier. Lastly, a 7.23 % difference between the output power of PV-ref and PV-PCM module is observed after 70 min. Hence, it can be concluded that the PCM effectively enhances the performance of PV systems. This improvement is expected to yield significant energy gains in large-scale solar power plants, particularly in hot and arid regions. Furthermore, it has the potential to extend the lifespan of PV modules, resulting in additional economic benefits.

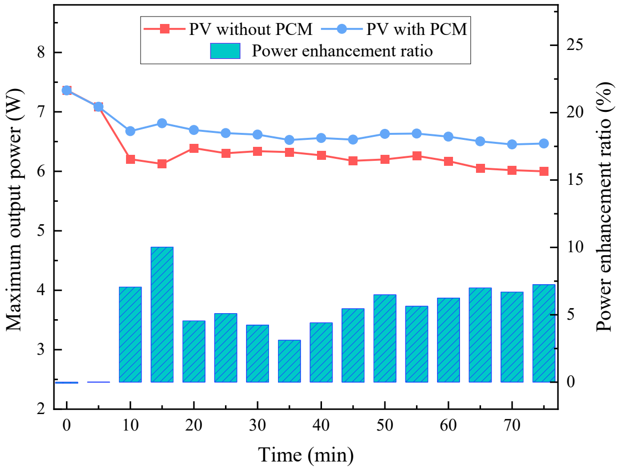

Fig. 9. Temporal evolution of maximum output power and power enhancement ratio.

4 Conclusion

This study investigated the impact of phase change material on the cooling of freestanding photovoltaic panels. For this purpose, a novel eutectic PCM was employed. An indoor experimental study was conducted to compare the performance of PV-PCM with the reference PV panel. Based on our findings, the main conclusions are as follows:

- A novel eutectic PCM was prepared and characterized using bio-based PCMs with 80 wt.% of lauric acid and 20 wt.% of oleic acid. The DSC results revealed that the prepared PCM has an appropriate phase change temperature and latent heat to cool a PV module.
- Integrating the prepared eutectic PCM on the backside of the PV panel can control its temperature under 67.81 °C for 3 hours under a radiation of 1000 W/m.

- The highest temperature is maintained in the upper part of the PV-PCM panel due to the natural convection effect.
- Further investigations are needed to enhance PCM stability and its thermophysical properties to address the temperature stratification problem in inclined PV-PCM panels.
- The PV-PCM system significantly improved the electrical power output compared to the reference PV panel, showing a 7.23% enhancement ratio after 70 minutes.
- A techno-economic assessment of a PV solar power plant enhanced with the prepared PCM needs to be conducted.

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