Use of Phase Change Material to enhance the Effectiveness of the Photovoltaic Module

Uso de Material de Cambio de Fase para potenciar la Efectividad del Módulo Fotovoltaico

Uso de Material de Mudança de Fase para aumentar a Eficácia do Módulo Fotovoltaico

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Summary. - The usefulness and productivity of photovoltaic (PV) panels are significantly impacted by ambient and operating temperatures. However, the negative influence of hot climates on PV panel performance can be mitigated through innovative cooling techniques. This research work aims to investigate the implementation of phase change material (PCM) on the backside of solar modules to reduce panel temperature and enhance energy production. A hybrid system utilizing soy wax for cooling is applied to the rear of the panel. Comparative data have been collected on various days, and the outcomes have been analyzed. The outcomes reveal that the usage of phase change material reduced panel temperature by up to 18°C, causing a 10.89% rise in electricity generation compared to panels without cooling systems.

Keywords: Photovoltaics; Solar irradiance; Cell temperature; Phase change material; Solar Energy.

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Resumen. - *La utilidad y productividad de los paneles fotovoltaicos (PV) se ven significativamente afectadas por las temperaturas ambiente y de funcionamiento. Sin embargo, la influencia negativa de los climas cálidos en el rendimiento de los paneles fotovoltaicos se puede mitigar mediante técnicas de refrigeración innovadoras. Este trabajo de investigación tiene como objetivo investigar la implementación de material de cambio de fase (PCM) en la parte posterior de módulos solares para reducir la temperatura del panel y mejorar la producción de energía. En la parte posterior del panel se aplica un sistema híbrido que utiliza cera de soja para enfriar. Se han recopilado datos comparativos en varios días y se han analizado los resultados. Los resultados revelan que el uso de material de cambio de fase redujo la temperatura del panel hasta 18°C, provocando un aumento del 10,89% en la generación de electricidad en comparación con los paneles sin sistemas de refrigeración.*

Palabras clave: *Fotovoltaica; Radiacion solar; Temperatura celular; Material de cambio de fase; Energía solar.*

***Resumo*. -** *A utilidade e a produtividade dos painéis fotovoltaicos (PV) são significativamente afetadas pelas temperaturas ambiente e de operação. No entanto, a influência negativa dos climas quentes no desempenho dos painéis fotovoltaicos pode ser mitigada através de técnicas inovadoras de arrefecimento. Este trabalho de pesquisa tem como objetivo investigar a implementação de material de mudança de fase (PCM) na parte traseira de módulos solares para reduzir a temperatura do painel e aumentar a produção de energia. Um sistema híbrido que utiliza cera de soja para resfriamento é aplicado na parte traseira do painel. Dados comparativos foram coletados em vários dias e os resultados foram analisados. Os resultados revelam que o uso de material de mudança de fase reduziu a temperatura do painel em até 18°C, causando um aumento de 10,89% na geração de eletricidade em comparação com painéis sem sistemas de refrigeração.*

Palavras-chave: *Fotovoltaica; Irradiância solar; Temperatura celular; Material de mudança de fase; Energia solar.*

1. Introduction . - The depletion of natural resources, especially fossil fuels, has become a significant worry for both developed and developing nations. Due to this, researchers are now trying to harvest energy through renewable energy sources with maximum efficiency [1]. Considering all renewable sources, solar energy has garnered the greatest attention [2]–[4]. Solar energy, an infinite and sustainable renewable resource, offers the potential for generating both thermal energy through a solar thermal (ST) system and electrical energy through a photovoltaic (PV) system [5]. Photovoltaic (PV) technology is experiencing rapid progress among all renewable energy sources due to its simplicity and cost-effectiveness in operation [6]. PV cells, unfortunately, can only transform 15 to 20 percent of solar irradiation into power [7]. The unutilized energy is dissipated as heat, leading to a surge in cell temperature. The performance of the photovoltaic module is notably influenced by its operating temperature [8]. The tendency of PV cells to transform solar radiation into electrical energy decreases as the working temperature upsurges, which has a direct relation with the ambient temperature. Consequently, the efficiency of the PV cell experiences a substantial reduction on hotter days [9]. The electrical efficiency of a PV cell decreases by almost 0.5% for every single 1°C rise in temperature [10].

By integrating a heat recovery system at the backside of the panel, the electrical efficiency can be better. This transformation turns the conventional PV system into a hybrid Photovoltaic/Thermal (PVT) scheme, capable of simultaneously generating electricity as well as heat from a solo integrated system. Various researchers have explored different cooling methods for PV panels, involving the use of diverse working fluids such as air, water, and PCM. Uzair et al. [11]–[13] researched optimizing PV panels and performed numerical simulations to analyze the ideal tilt angles for enhanced performance. Kim et al. [14] researched improving the overall efficiency of PV units by implementing air cooling. Their findings indicated that, on average, the system attained a thermal efficiency of approximately 20% and an electrical efficiency of 15%. Diwania et al. [15] performed a experiments to boost the overall efficiency of PV modules using a V-type air channel. Their research was specifically carried out for the climate conditions of Ghaziabad, India. The findings revealed that the hybrid system was capable of converting approximately 10.3% of sunlight into electricity and 41.5% into heat, resulting in an overall system efficiency of around 52%. In our previous study [7], we achieved an enhancement in the efficiency of PV modules by transforming them into hybrid PVT modules. This was achieved by integrating a wooden air duct at the backside of the module. As a result of this implementation, the electrical efficiency was measured at 14.8%, while the thermal efficiency reached an impressive 65.6%.

Indeed, water can be a more effective option for heat removal than air due to its higher thermal conductivity. Water's ability to conduct heat more efficiently allows for improved cooling of PV modules, making it a favourable choice for certain cooling systems. According to Aste et al. [16], who utilized a specially designed PVT water collector, water-cooled PV systems displayed more electrical efficiency when performance was compared with air-cooled PV systems. Sardouei et al. [17] explored the effects of water flow rate on the production of PVT systems. They experimented with flow rates varies in the range of 30 L/h and 90 L/h and found that a water flow rate of 90 L/h led to a remarkable thermal efficiency of 56%. Yazdanpanahi et al. [18] conducted a comprehensive investigation into the energy efficiency of water-cooled PV systems using both experimental and computational approaches. Their research demonstrated a strong agreement among the computational and investigational results. Furthermore, they found that a flow velocity of 2 g/s resulted in a extreme electrical efficiency of 14 percent.

In recent times, PV cooling by Phase Change Material (PCM) has garnered significant attention [19]–[22] due to its distinct advantages over air- and water-cooling methods. Indeed, Phase Change Material (PCM) can absorb more heat compared to air and water, leading to a greater reduction in cell temperature. This characteristic makes PCM-based cooling an attractive option for enhancing the efficiency and performance of PVs. In both air- and water-cooled PV systems, the need for pumping devices to maintain a continuous flow of fluid results in energy consumption. According to Najjar et al. [23], the utilization of metal foam as a PCM can effectively reduce the cell temperature by approximately 12°C. To boost the productivity of PV systems, Hasan et al. [24] conducted a study that involved investigating five different PCMs, namely capric-lauric acid (C-L), capric-palmitic acid (C-P), paraffin wax (RT20), commercial mix (SP22) and a pure salt hydrate ($CaCl2.6H2O$). Their discoveries revealed that the utilization of PCM successfully dropped the temperature of PVs by an impressive 18°C. According to Indartono et al. [25], petroleum jelly can be effectively employed as a Phase Change Material (PCM) for the heat management of PVs. When applied to the rare surface of the PV plate, petroleum jelly effectively absorbs thermal energy from the plate. The study found that petroleum jelly was particularly effective in reducing cell temperature, resulting in an impressive increase in electrical efficiency of approximately 7.3%. In a comparative study conducted by Stropnik and Stritih [26], they examined a standard PV module and a customized PV module integrated with an RT28HC PCM. The results exposed that the cell temperature in the simple PV plate was approximately 36°C more when compared with the plate having PCM cooling.

Additionally, they found that the PCM-cooled PV system generated power at a rate that was 7.3% higher than the simple PV module. This suggests that the incorporation of PCM cooling can meaningfully enhance the efficiency and presentation of PV systems. In an attempt to progress the overall efficiency of PV systems, Xu et al. [27] utilized fatty acids as PCM. The study revealed that this approach led to a remarkable increase in electrical efficiency by 22.2%. The use of fatty acids as PCM proved to be a promising method for enhancing the performance of PV modules and optimizing their energy output.

Indeed, the explanations provided earlier highlight the standing of cooling PV units to improve the overall effectiveness of the system. While air and water can also be used for cooling, PCM stands out as the most efficient approach to increase electrical efficiency and lower cell temperature. The usage of PCM as a cooling method had demonstrated significant advantages, making it a preferred choice for enhancing the performance and efficiency of PV systems. In this study, soya wax is being utilized as a Phase Change Material (PCM) for the first time to enhance the electrical efficiency of PV panels. Since soya wax is derived from natural materials and extracted from soybeans, its use poses no risk to the environment. The investigation involves two panels: one is cooled by incorporating soy wax on the back side of the plate, while the other remains unmodified. The cell temperature and electrical efficiency of both panels are measured on different days to analyze and compare the effects of using soya wax as PCM. This research aims to assess the potential of soya wax as an efficient and eco-friendly cooling method to advance the performance of PV systems.

2. Methodology. - For the investigation, two monocrystalline PV modules, each rated at 30 Watts, were sourced from the local electrical market in Karachi. The modules' specifications are detailed in Table 1.

Maximum Rated Power (P_{max})	30 W
Output Tolerance	±3.0 %
Current at Maximum Power (I_{mp})	1.93 Amps
Voltage at Maximum Power (V_{mp})	17.5 Volts
Short Circuit Current (I_{sc})	1.93 Amps
Open Circuit Voltage (V_{oc})	21.07 Volts
Nominal Operating Cell Temperature (NOCT)	47^{o} C

Table I. Specifications of PV module used.

To improve their electrical efficiency, Soya Wax, with a melting point of approximately 45°C, was utilized as the Phase Change Material (PCM) at the rear side of the solar plate. For this setup, 4 kg of Soya Wax had been used as PCM. To support and hold the Soya Wax in place, an aluminum sheet was utilized. Approximately 10% of the space was left unfilled to accommodate thermal expansion during the phase change process. Figure 1 illustrates the actual experimental setup, while Figure 2 showcases the backside of the panel equipped with PCM.

Both panels were positioned at a tilt of approximately 25°, which is roughly equivalent to the latitude of city Karachi. This angle is chosen to capture the maximum possible solar radiation efficiently.

Experiments were conducted on 10 different days throughout the calendar year. These experiments aim to gather data and observe the performance of the PV panels equipped with Soya Wax as PCM under varying weather and solar radiation conditions throughout the year in Karachi. During the experiments, the instantaneous solar radiations were measured using a Pyranometer, which provided real-time data on the solar energy received by the PV plates. Simultaneously, the instantaneous cell temperature of both panels was monitored to judge the impression of Soya Wax as PCM on temperature reduction. To understand the electrical performance, the power output from both PV modules was determined by employing a variable load. Figure 3 displays the solar radiation data collected on the experimental days.

Figure I. Two panels, the right one is equipped with PCM while the left is without PCM.

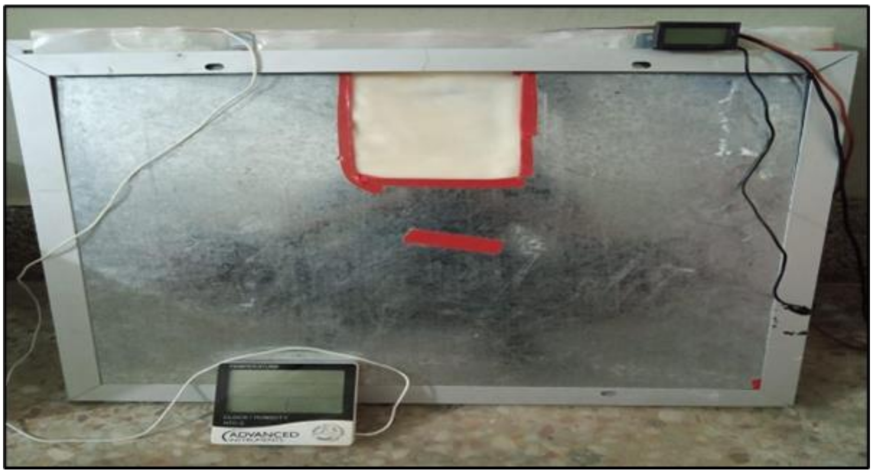

Figure II. Back side of the PV plate is equipped with an Aluminum sheet.

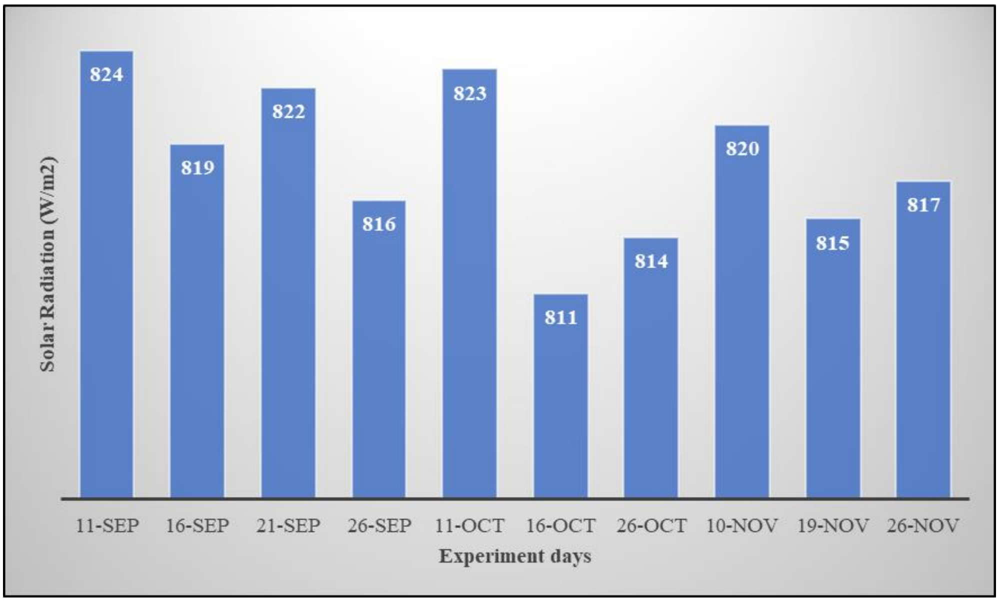

Figure III. Solar irradiance on different days

The cell temperature of the PV plate was calculated by using the following relation

$$T_{cell} = T_{amb} + \left(\frac{NOCT-20}{0.8}\right) \qquad \text{Equation 1}$$

Where T_{cell} is the cell temperature, T_{amb} is the ambient temperature and NOCT is the Nominal Operating Cell Temperature, which is given in Table 1.

The temperature-adjusted power from the PV module was calculated by

$$P_T = P_R(1 - C_T(T_{cell} - 25)) \qquad \text{Equation 2}$$

Here, P_T is the temperature-adjusted power, P_R is the rated power given in Table 1 and C_T is the temperature coefficient taken to be 0.5%/ºC [28]

The actual power drawn from both panels had been determined by

$$P = I \times V \qquad \text{Equation 3}$$

Here, P is the actual power produced by the panel, I is the current from PV while V is the voltage produced by the PV plate

The efficiency of the PVs had been determined by

$$\eta = \frac{P\ electrical}{P\ irradiance} = \frac{I \times V}{E \times A} \times 100\% \qquad \text{Equation 4}$$

Here, E is the solar radiation incident on the panel, which is given in Figure 3 while, A is the area of the collector.

3. Result and Analysis. - During the experiments conducted on 10 different days throughout the calendar year, both PV panels were placed side by side at a tilt of approximately 25°, which corresponds to the latitude of Karachi. This angle was chosen to maximize solar energy incident on the PV plates. The temperature of both panels was measured using an infrared thermometer and compared, as shown in Figure 4. The outcomes indicate that the PV plates' temperature is highly dependent on the surrounding temperature. Theoretical temperature calculations of the PV plate were performed using Equation 1. Figure 4 clearly illustrates that the PV panel equipped with Soya Wax as PCM exhibits lower temperatures compared to the plate without PCM cooling. This temperature difference arises from the efficient heat transfer among the PV plate and the PCM. When the PV module's temperature increases, the high-temperature difference facilitates the transfer of heat to the PCM, causing a cut in the PV panel's temperature while rising the PCM temperature. On the other hand, the PV panel without PCM lacks a heat sink mechanism, resulting in significantly higher temperatures compared to the PV panel with PCM cooling. On average, the temperature of the PV panel with PCM is approximately 22°C lower than that of the panel without PCM, as depicted in Figure 5. These findings emphasize the significant cooling effect of Soya Wax as PCM.

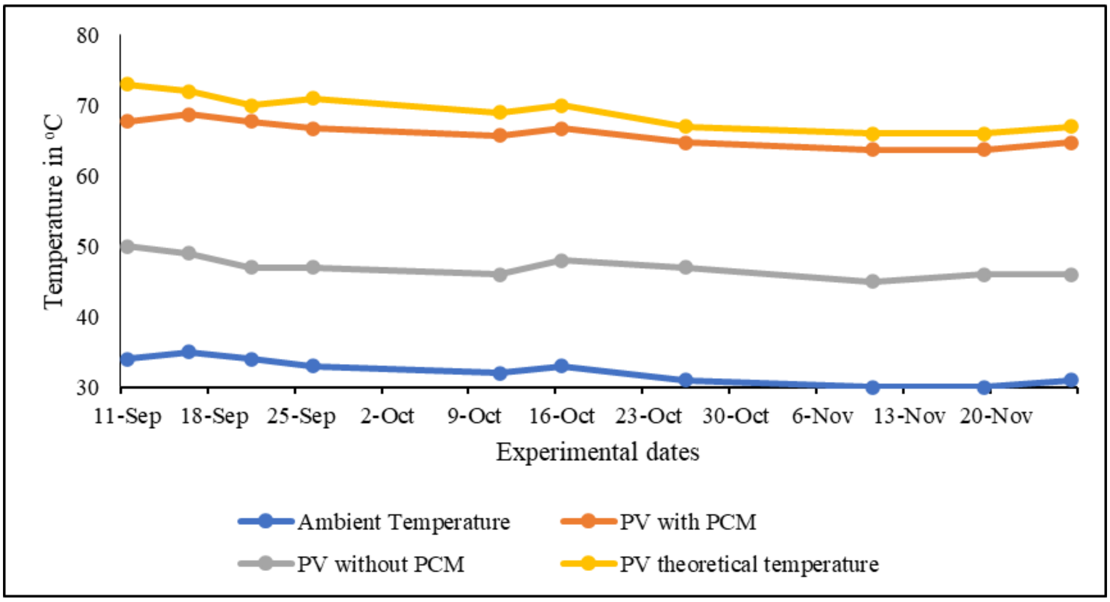

Figure IV. Temperature distribution of panels on experimental days

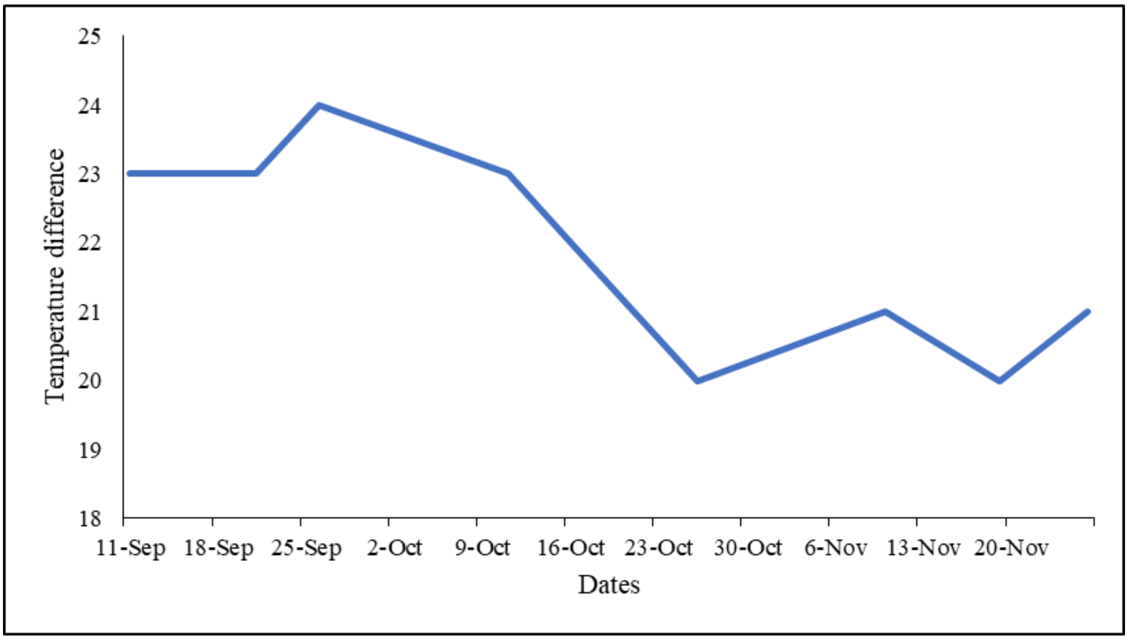

Figure V. The temperature difference between panels

In addition to measuring the actual cell temperature, the theoretical power generated by the PV plates was also computed using equation 2, considering both the theoretical cell temperature and the actual cell temperature. The results of this calculation are presented in Figure 6. From where it is evident that the PV panel equipped with Soya Wax as PCM extracts the maximum power. On average, the PV panel with PCM can generate approximately 14% more power compared to the panel without PCM. This notable difference in power generation is attributed to the cooling effect provided by Soya Wax as PCM. While both the panels are subjected to the identical ambient conditions, the PV plate equipped with PCM has the advantage of continuously transferring heat to the PCM, leading to a reduction in its temperature. Consequently, this cooling effect results in higher power production as compared to that of plate without PCM. On the other hand, the panel without PCM is producing less power than the temperature-adjusted power of the PV module. This discrepancy occurs because the genuine temperature of the PV plate without PCM is more than the theoretic temperature, as observed in Figure 4. Overall, the results from Figure 6 underscore the significant impact of Soya Wax cooling on the electrical performance of the PV panels, showcasing its ability to enhance power production and increase the total effectiveness of the PV system.

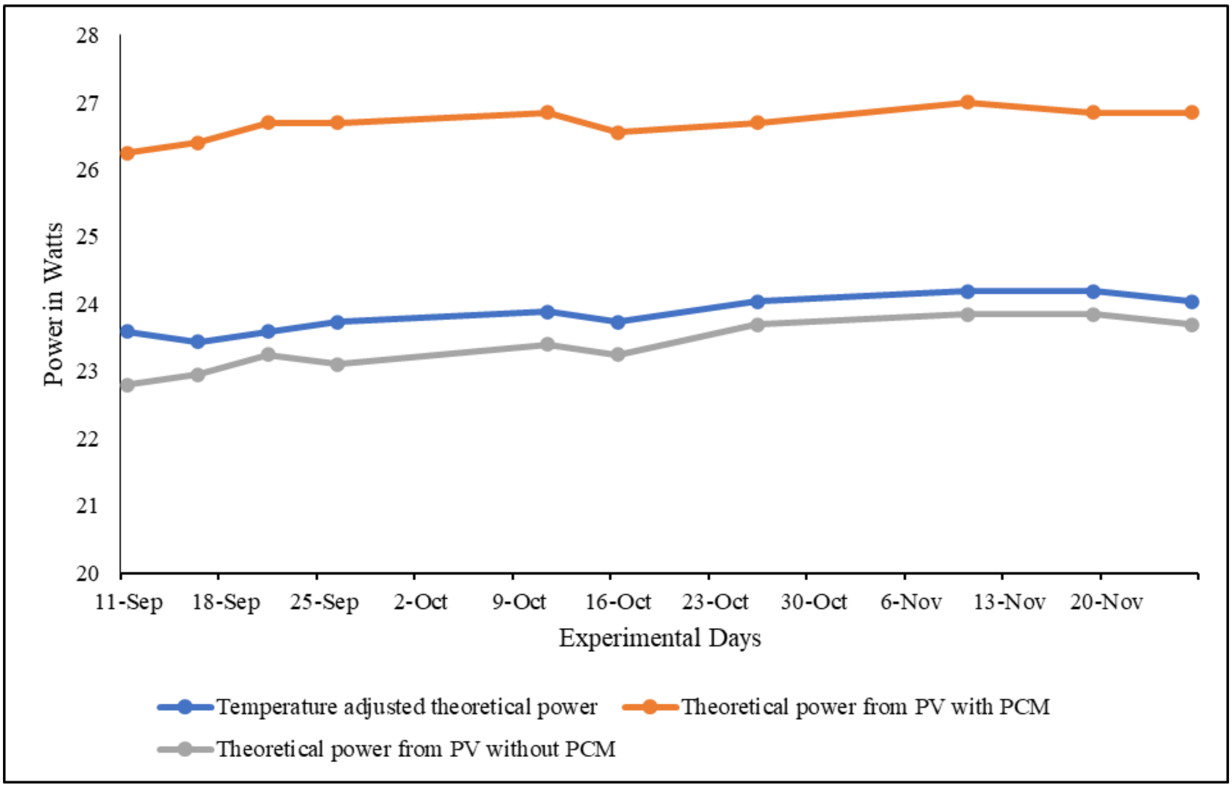

Figure VI. Theoretical power from panels

Using equation 3, the electric power generated by both panels was calculated based on the measured voltage and current at experimental dates, obtained using a Multimeter. Figure 7 illustrates the outcomes, clearly displaying that the PV plate equipped with Soya Wax as PCM produces more power compared to the plate without PCM. On average, the PV plate with PCM generates approximately 9.7% more power than the panel without PCM. This notable increase in power output is directly attributed to the cooling effect provided by Soya Wax as PCM. The cooling mechanism enabled by the PCM significantly decreases the operating temperature of the PV plate, leading to upgraded electrical efficiency and enhanced power generation.

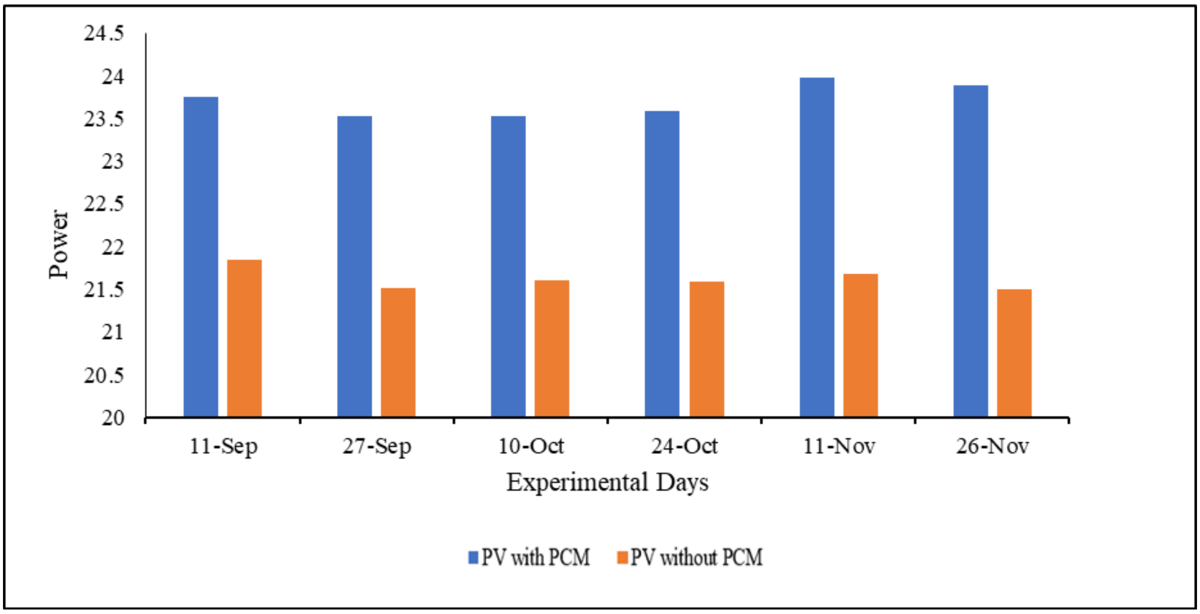

Figure VII. Power from PV panels

Figure 8 illustrates the relationship between current and voltage for both PV panels. The IV curve shows the power obtained from the PV-PCM system and the PV system without PCM. The extreme power gotten from the PV-PCM system is 21.51 W, whereas the PV system without PCM produces 19.4 W. This indicates a clear surge in the electrical power of the PV module when Soya Wax is used as PCM for cooling. At the points corresponding to the maximum power, the PV-PCM system has a current of 1.23 A and a voltage of 17.49 V, while the PV system without PCM has a current of 1.18 A and a voltage of 16.44 V. The results further confirm the effectiveness of Soya Wax as PCM in enhancing the electrical effectiveness and power production of the PV plate. The cooling provided by the PCM enables the PV-PCM plate to operate at higher power levels compared to the plate without PCM cooling, leading to an overall improvement in the performance and effectiveness of the PV plate.

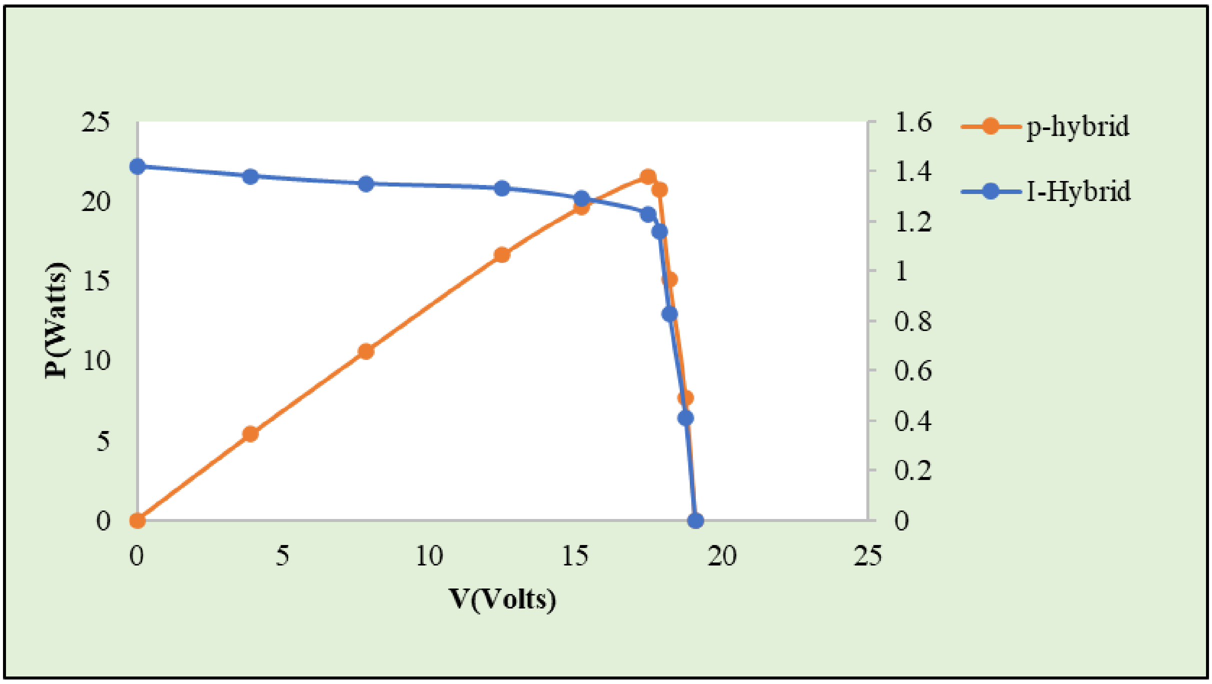

Figure VIII. (a) IV curve of PV-PCM with Voltage, current, and power profile

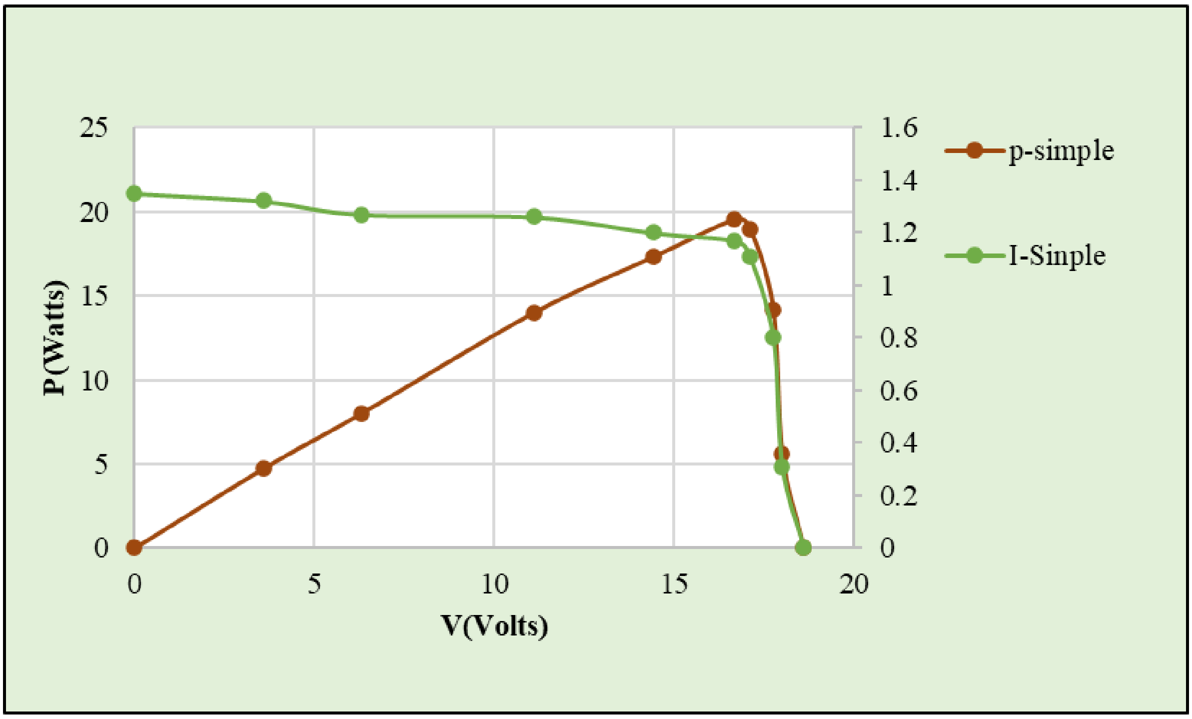

Figure VIII. (b) IV curve of PV-Simple with Voltage, current, and power profile

4. Conclusion. - This study aimed to explore the effectiveness of using PCM as a coolant to adjust the cell temperature of PV modules. Two different configurations of PV panels were considered for the experiments. One panel was kept simple, while the second configuration integrated PCM to provide cooling. The PCM used in the experiment was Soya wax. As the solar panels absorbed heat, the soya wax began to melt, transitioning from a solid to a liquid state. This heat absorption significantly improved the electric power production capability of solar panels. The results revealed a remarkable 31.25% reduction in solar cell temperature, from 64°C in the panel without PCM to 44°C in the panel with PCM cooling. This drop in cell temperature resulted in the maximum electric power outputs of 21.5 W and 19.4 W for the PV-Hybrid and PV-simple configurations, respectively. Data was collected for different ten days, and it was observed that PV with PCM constantly produced more electrical power when compared with the simple PV plate. The integration of PCM to absorb thermal energy from the solar plate backplane effectively lowered the panel's surface temperature, leading to an increase in electric power output. This technical evaluation of the hybrid PVT system demonstrated that employing PCM at the panel's backside is a promising approach to boost power outputs while also lowering the cell temperature. Overall, the study highlights the significant impact of soya wax in enhancing the effectiveness and power generation of PV modules, presenting a viable and theoretically possible solution to progress the performance of PV plates.

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Nota contribución de los autores:

1. Concepción y diseño del estudio
2. Adquisición de datos
3. Análisis de datos
4. Discusión de los resultados
5. Redacción del manuscrito
6. Aprobación de la versión final del manuscrito

MF ha contribuido en: 1, 2, 3, 4, 5 y 6.
AAN ha contribuido en: 1, 2, 3, 4, 5 y 6.
MU ha contribuido en: 1, 2, 3, 4, 5 y 6.

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