

Performance Enhancement of Photovoltaic Panels via Dual Innovative Cooling Strategies

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Abstract

Photovoltaic (PV) panel performance is significantly affected by operating temperature, with higher cell temperatures reducing efficiency and accelerating degradation. In hot climates, effective cooling is crucial to sustain energy yield. This study evaluates the combined use of Phase Change Material (PCM) and aluminium fin heat sinks as a passive cooling strategy. The PCM absorbs excess thermal energy during melting, delaying temperature rise, while the fins increase surface area for convective heat dissipation. Experimental tests compared a reference PV module, a PV with PCM, and a PV with PCM plus fins. The PCM + fins configuration reduced the average module temperature from approximately 41.00°C (without cooling) to 37.15°C, a decrease of about 3.85°C. This reduction improved average module efficiency from 2.87% in the reference PV to 3.50%, representing a relative gain of 21.95%. Besides, the power output analysis showed that PCM + fins performed slightly lower in the early morning due to cooler ambient conditions, but during peak irradiance, it maintained higher voltage levels and minimized thermal losses, outperforming PCM alone. This resulted in more stable electrical parameters and improved daily energy yield. The results demonstrate that integrating PCM with aluminium fins is an effective, low-cost passive cooling method for PV panels in hot climates, while enhancing performance.

Keywords

Passive Cooling, Phase Change Material, Fins Heat Sink, Temperature Reduction, Photovoltaic Performance

1. Introduction

Environmental concern towards the rise of global warming has become a pro-

found long-term issue worldwide [1]. The energy generation from fossil fuels accounts for a significant greenhouse gas contribution, rising at an accelerating rate since the industrial revolution. Thus, in-depth research on alternative energy resources emerged, aiming to support climate change policies and mitigations. Recent trends in global energy-related CO₂ emissions remain crucial, with an increment of 1.9% [2]. However, without progressive action for adequate regulatory frameworks and research, carbon-related emissions will double by 2050. As the world moves toward more sustainable energy solutions, solar photovoltaic (PV) technology has become one of the most promising and widely used forms of renewable energy.

One of the critical problems with the commercial PV panel is the performance degradation caused by the elevated panel operating temperature above standard testing conditions (STCs). A significant portion of absorbed solar irradiance cannot be converted into electricity but dissipated as heat [3]. The dissipated thermal energy in a PV panel heats the components such as solar cells, electrodes, solders, busbars, wires, and sealants, giving rise to the panel operating temperature. It was found that regions with high altitudes exhibit a higher performance ratio due to low temperature and vice versa [4] [5]. Thus, the challenge has been more crucial in areas that receive higher solar irradiance throughout the year [6]. The study suggests that module conversion efficiency enhancement could be achieved by reducing the panel operating temperature. It was reported that the degradation rate of the PV panel doubles for every 10°C increase in its operating temperature [7]. According to the report presented by IEA-PVPS T13-01:2014, the most critical failure was recorded due to the accelerated thermal cycling test (18%). An effective way to counteract the rate of thermal degradation of a PV module is by reducing its surface temperature. Therefore, an effective PV cooling method is necessary to enhance the PV power generation and ensure its long-term reliability.

In this work, passive cooling of PV panels through a dual innovative cooling strategies that combines aluminum fin heat sinks and Phase Change Material (PCM). The aluminum fins, designed with a rectangular geometry, enhance heat transfer from the rear surface of the PV panel, while the PCM enclosed in a novel multi-height configuration. Unlike conventional constant-thickness PCM casings, the multi-height design is tailored to match the thermal behavior of the PV panel, thereby improving cooling efficiency. The proposed dual cooling system is evaluated under real outdoor operating conditions to assess its effectiveness in reducing PV panel temperature and enhancing electrical performance.

2. Theoretical Background

Electrical Performance Characteristics

The operating temperature of a PV panel plays a vital role in the energy conversion process. Various methods have been proposed in the literature to determine the panel operating temperature through simplified working equations. The following Equation (1) is widely used to determine the module efficiency [8].

$$\eta = \eta_{\text{STC}} \left[1 - \beta (T_{\text{PV}} - T_{\text{STC}}) \right] + \gamma \log G \quad (1)$$

η_{STC} is the efficiency at temperature of 25°C, G is the solar irradiance measured in W/m², and T_{PV} is the PV panel temperature. β and γ are the coefficients for the temperature and solar irradiance, respectively. These values are taken directly from the PV panel datasheet provided by the manufacturer, ensuring that the calculations reflect the panel's specified behavior under varying temperature and irradiance conditions. However, in most cases γ denotes as 0 and expressed as [9],

$$\eta = \eta_{\text{STC}} \left[1 - \beta (T_{\text{PV}} - T_{\text{STC}}) \right] \quad (2)$$

The rated power output provided by the manufacturer under Standard Test Conditions (STC) rarely matches the actual power produced in the field. Based on [10], Equation (3) is widely used to estimate the power output of PV panel under real operating conditions.

$$P_{\text{out_roc}} = P_{\text{STC}} \times k_{\text{temp}} \times k_G \quad (3)$$

$P_{\text{out_roc}}$ is the actual power output produced in the test site, P_{STC} is the rated power output based on manufacturer's datasheet, k_{temp} is derating factor due to module temperature, and k_G is derating factor due to irradiance.

3. Experimental Setup

In this paper, Paraffin-32 and aluminium fins are integrated to provide novel cooling

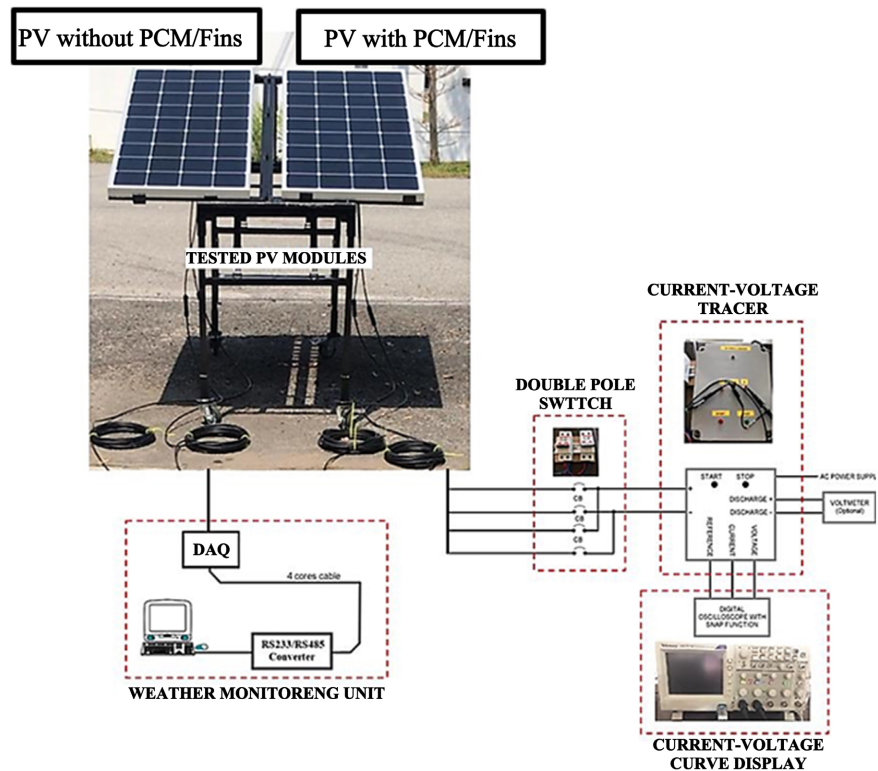


Figure 1. An outdoor experimental setup consists of two identical PV panels.

techniques to improve PV performance. PCM helps to maintain a more constant and lower working temperature by taking in extra heat from the PV panels. Besides, the attached aluminum fins further improves convective heat dissipation to the surrounding based on Newton's Law of Cooling. This dual mechanism helps to regulate the PV panel temperature. As illustrated in **Figure 1**, the experimental setup was conducted under outdoor conditions of Malacca, Malaysia (2.1896°N, 102.2501°E). The setup consists of two identical polycrystalline panels (150 Wp), a weather monitoring unit, and a current-voltage measurement unit.

3.1. Selection of Phase Change Material (PCM) and Design Geometry

The paraffin-based PCM was selected in this project has a melting point of 32°C. The primary melting peak is observed at approximately 29.6°C, with an onset temperature of 27.0°C and an end temperature of 32.0°C, closely aligning with the target operating range for panel cooling. This melting range ensures that the PCM can effectively absorb excess heat generated during peak irradiance [11].

Previous studies have demonstrated varying degrees of success in PV-PCM integration. However, these designs typically employed PCM casings of constant thickness, which can lead to uneven thermal regulation across the PV surface. Building on this limitation, the present study proposes a multi-height PCM casing in combination with fin heat sinks to ensure more uniform temperature regulation across the PV panel. The PCM casing geometry is illustrated in **Figure 2**.

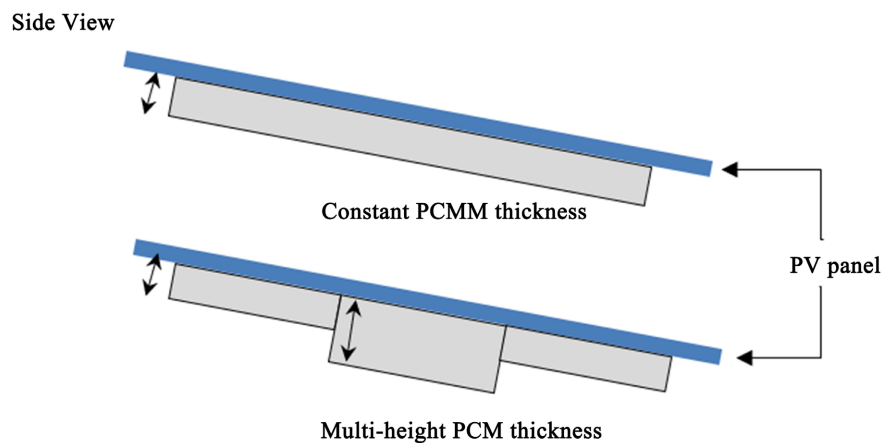


Figure 2. Side view comparison of constant-thickness and multi-height PCM casing designs.

3.2. Design Configuration of Aluminum Fin Heat Sinks

Aluminum fin heat sinks offer an effective means of enhancing heat transfer in regulating panel temperature. Fins are often preferred due to their cost-effectiveness, low maintenance needs, and high thermal performance. In this study, rectangular fins were employed (see **Figure 3**) to maximize surface area contact with

the PCM and the rear surface of the panel, thereby facilitating efficient heat dissipation and improving the overall cooling performance (**Table 1**).

Table 1. Rectangular fin design specifications.

Parametric measurements	Dimensions (mm)
Fin length	800
Fin spacing	45
Fin thickness	1.0

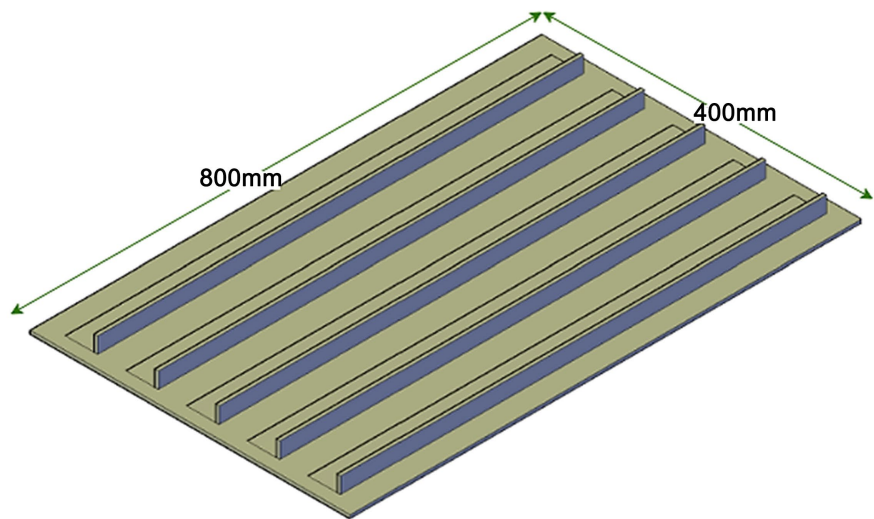


Figure 3. Rectangular aluminum fins design.

4. Results and Discussions

Numerous testing sets were conducted outdoors in the Faculty of Technology and Electrical Engineering, UTeM, Malaysia. All tests were performed simultaneously under clear blue sky to ensure a reliable comparison between reference and modified PV panels. Besides, this guaranteed the evaluation reach the necessary level for performance monitoring aligned with Malaysia Standards MS1837:2018.

4.1. The Effect of Dual Cooling on Electrical Performance Characteristics

The effect of the cooling system on the electrical output of the PV panels was investigated, and it was found that lower operating temperatures significantly improved performance. The cooling system increased the energy conversion efficiency of the panels, which led to a higher electrical output, by sustaining lower and more consistent temperatures.

The measurements comprise several important electrical parameters, including short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), current at maximum power (I_{mp}), and voltage at maximum power (V_{mp}), as recorded in **Table 2** and **Table 3**.

Table 2. Performance characteristics of PV reference panel.

Time (h)	Irradiance (W/m ²)	Module temperature (°C)	Isc (A)	Voc (V)	Imp (A)	Vmp (V)	Electrical efficiency
10:00	473	39.6	3.91	19.80	3.28	14.89	2.51%
10:30	425	39.7	3.58	19.80	2.88	15.88	2.35%
11:00	556	40.0	4.17	19.87	3.57	15.09	2.77%
11:30	660	40.3	5.38	19.79	3.50	15.79	2.85%
12:00	880	44.4	7.11	19.91	6.06	14.17	4.42%
12:30	508	42.2	3.89	19.86	2.99	15.14	2.33%

Table 3. Performance characteristics of PV panel + PCM + Fins.

Time (h)	Irradiance (W/m ²)	Module temperature (°C)	Isc (A)	Voc (V)	Imp (A)	Vmp (V)	Electrical efficiency
10:00	473	37.1	4.11	19.85	3.54	14.40	2.62%
10:30	425	38.7	3.86	19.91	3.36	14.89	2.58%
11:00	556	35.3	4.74	20.01	3.99	15.25	3.13%
11:30	660	37.3	5.73	20.03	4.84	14.57	3.63%
12:00	880	37.7	7.78	19.96	6.66	14.54	4.64%
12:30	508	36.8	7.48	19.88	6.11	14.06	4.42%

The application of PCM combined with fins resulted in a notable reduction in the average PV module temperature from approximately 41.00°C (without cooling) to 37.15°C. This reduction of around 3.85°C can be attributed to the synergistic effects of the two passive cooling strategies. The PCM absorbs excess thermal energy during its melting process, delaying the rise in module temperature, while the fins increase the surface area for heat dissipation, enabling more efficient convective heat transfer to the surrounding environment. By maintaining the module at a lower temperature, the system operates closer to its optimal thermal conditions, reducing thermal stress and performance degradation.

In terms of electrical performance, the cooling strategy improved the average module efficiency from 2.87% in the reference PV to 3.50% with PCM + fins, representing an absolute gain of 0.63 percentage points or a relative improvement of approximately 21.95%. This enhancement is primarily due to the reduced cell temperature, which minimizes the adverse impact of the temperature coefficient on voltage and power output. The cooling system ensured better stability of electrical parameters such as Voc and Vmp, particularly under high irradiance conditions, thereby increasing the overall energy yield. These findings highlight the effectiveness of integrating PCM and fins as a passive cooling solution to boost PV module performance in hot climate applications.

4.2. The Effect of Module Temperature Reduction on Power Output

The effect of module temperature reduction on power output is evident when comparing the PV module with PCM alone to the PV module with PCM and fins across different times of the day. Based on **Figure 4**, the PV-PCM configuration produced a higher power output of 56.75 W compared to 50.98 W for the PV-PCM/Fins configuration. This slight underperformance of the PCM + fins setup in the early morning can be attributed to the lower irradiance and relatively cooler ambient conditions, where the additional cooling effect of fins is less critical, and in some cases, may cause the module to operate slightly below its optimal temperature range.

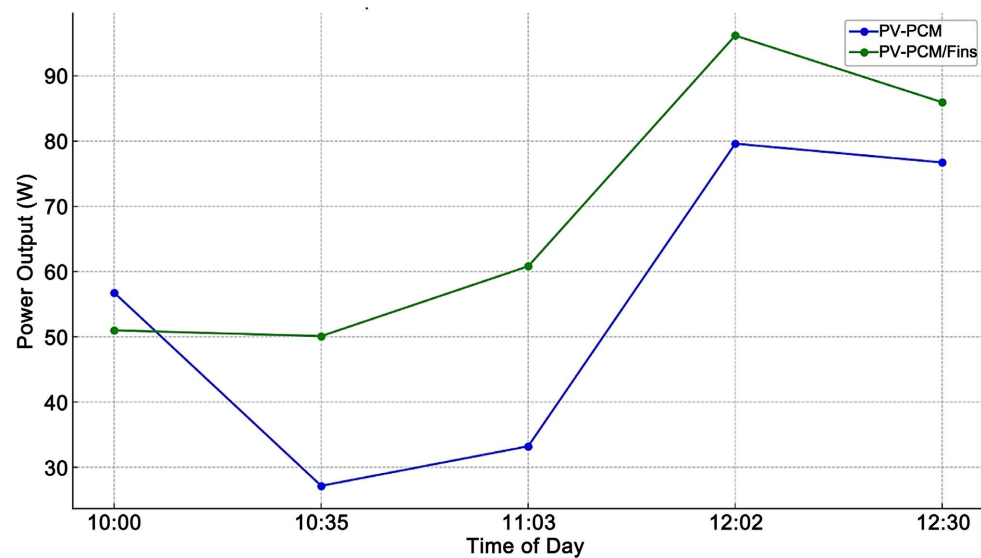


Figure 4. An outdoor experimental setup consists of two identical PV panels.

However, as the day progresses and irradiance increases, the benefit of enhanced cooling becomes more pronounced. The PCM + fins configuration effectively limits the rise in module temperature, reducing thermal losses and maintaining higher voltage levels, which directly improves power generation. This advantage is particularly significant during peak solar hours when the PV-PCM configuration experiences more rapid temperature increases, leading to a steeper decline in power output. Consequently, while the PCM + fins system may start with a slightly lower output in the morning, it sustains better performance under high-temperature conditions, resulting in an overall improvement in daily energy yield.

5. Conclusions

This study demonstrates that integrating Phase Change Material (PCM) with aluminum fin heat sinks is an effective passive cooling strategy to enhance photovoltaic (PV) panel performance in hot climates. The PCM + fins configuration successfully reduced the average module temperature by approximately 3.85°C compared to the reference module, resulting in a relative efficiency gain of 21.95%.

Experimental results showed that this configuration stabilizes electrical parameters, maintains higher voltage during peak irradiance, and improves daily energy yield compared to PCM alone or the reference PV. Overall, the findings confirm that combining PCM with fins provides a low-cost, reliable, and practical method for thermal management, offering a viable approach to improve PV efficiency and extend module lifespan in real-world outdoor conditions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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