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Experimental Investigation of Hybrid PCM–Finned Thermal Management System for Improving Photovoltaic Panel Performance

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Abstract

The operating temperature of photovoltaic (PV) modules is an important parameter which affecting their electrical performance and energy conversion efficiency. Under high solar irradiance, a substantial portion of the incident solar radiation is converted into heat, resulting in an increase in PV module temperature and reduction in electrical output. Phase change materials (PCMs) provide a passive method for thermal regulation by absorbing heat through latent heat storage during phase transition. However, the relatively low thermal conductivity of many PCMs can restrict heat transfer and reduce the effective utilization of the stored latent heat. The incorporation of aluminium fins provides an effective method of enhancing heat transfer within the PCM. The present study experimentally investigates the influence of aluminium fin spacing on the thermal and electrical performance of a PCM-integrated photovoltaic panel under variable solar irradiance conditions. Three fin-spacing configurations are proposed while maintaining constant PV module characteristics, PCM type, PCM mass, fin material and fin dimensions. A conventional PV panel and PCM-integrated PV configurations are used as reference cases. Solar irradiance, ambient temperature, PV surface temperature, PCM temperature, voltage and current are measured simultaneously during the experiments.

Electrical power and conversion efficiency are calculated from the measured electrical parameters. The temperature reduction, power improvement and cumulative energy generation are evaluated for the different fin-spacing configurations. The experimental results are intended to establish the influence of fin spacing on heat transfer between the photovoltaic module and PCM and to identify a suitable fin arrangement for passive thermal management. The study provides an experimentally based approach for improving PV performance through optimization of PCM-assisted conductive heat transfer without continuous auxiliary cooling power.

Keywords- Photovoltaic panel, Phase change material, Aluminium fins, Fin spacing, Passive cooling, Thermal management, Solar irradiance, PV efficiency, Latent heat storage.

1. INTRODUCTION

The increasing demand for clean and sustainable energy has accelerated the deployment of photovoltaic technology for electricity generation. Photovoltaic systems directly convert solar radiation into electrical energy and can be installed over a wide range of scales, from small standalone systems to large utility-scale solar farms. Despite their advantages, photovoltaic modules experience significant thermal loading during operation. A PV module receives solar radiation over its exposed surface. Only a portion of the incident solar energy is converted into electrical energy, while the remaining energy contributes to thermal generation within the module. Consequently, the temperature of a PV module can become substantially higher than the surrounding ambient temperature, particularly under high solar irradiance. The increase in PV cell temperature generally results in a reduction in electrical conversion efficiency. Therefore, thermal management is an important approach for improving the electrical performance and reliability of photovoltaic systems. Various cooling methods have been developed for PV modules. Active techniques include forced-air cooling, water circulation and other fluid-based systems. Although active cooling can provide effective heat removal, it requires pumps, fans, piping or other auxiliary components and may consume a portion of the generated electrical energy. Passive thermal management provides an alternative approach because it can operate without continuous external energy consumption. Phase change materials are particularly attractive for passive PV thermal regulation because they can absorb a considerable amount of thermal energy during melting through latent heat storage.

The application of PCM to photovoltaic systems has been widely investigated. Reviews have reported that PCM integration can reduce PV operating temperature and potentially improve electrical efficiency, while also identifying PCM thermal conductivity, material selection, encapsulation, cost and long-term stability as important challenges. One major limitation of many PCMs is their relatively low thermal conductivity. Heat transferred from the PV module may therefore remain concentrated near the PCM interface, resulting in non-uniform temperature distribution and incomplete utilization of the PCM volume. Thermally conductive fins can provide an effective solution to this limitation. Aluminium fins can conduct heat away from the PV rear surface and distribute it into a larger volume of PCM. The performance of a fin-assisted PCM system depends on several geometrical parameters, including fin height, fin thickness, number of fins and spacing between adjacent fins.

Previous experimental studies have demonstrated the potential of combining PCM with fins for PV thermal regulation. Atkin and Farid experimentally investigated PCM-infused graphite with an external finned heat sink and reported that the combined thermal-management arrangement provided substantial improvement compared with individual thermal-regulation configurations. More recently, Refaey et al. experimentally investigated different PCM materials and fin configurations under solar radiation intensities of 510, 680 and 850 W/m². Their results demonstrated that both PCM selection and fin geometry influence PV temperature and electrical performance. These studies demonstrate the importance of fin-assisted PCM systems but also indicate that fin geometry remains an important design variable. Recent reviews emphasize that fin spacing, fin dimensions, material properties and operating conditions can significantly influence heat transfer in PV–PCM systems. Therefore, the present work focuses specifically on the experimental investigation of **aluminium fin spacing** in a PCM-based PV thermal-management system. Unlike a broad comparison of different cooling technologies, the present study maintains the PCM material, PCM mass, fin material and fin dimensions constant while varying only the spacing between the fins.

2. LITERATURE REVIEW

The operating temperature of photovoltaic (PV) modules is an important parameter governing their electrical performance. During outdoor operation, a considerable fraction of incident solar radiation is converted into heat rather than electricity, resulting in an increase in PV cell temperature. Since the electrical conversion efficiency of PV modules generally decreases with increasing cell temperature, effective thermal management is essential for maintaining electrical output and improving the overall performance of photovoltaic systems. Various cooling techniques, including active and passive methods, have therefore been investigated. Among these techniques, phase change materials (PCMs) have received considerable attention because they can absorb and store thermal energy as latent heat during the phase-transition process [1–3].

Early studies demonstrated the potential of PCM to limit the temperature rise of PV modules. Huang et al. investigated PCM-based thermal regulation for building-integrated photovoltaic systems and demonstrated that PCM can absorb excess thermal energy during the melting process, thereby suppressing the temperature rise of the PV module [2]. Hasan et al. experimentally evaluated different PCMs for thermal regulation of building-integrated photovoltaic systems and showed that PCM melting temperature, latent heat and thermal properties strongly influence the thermal behaviour of PV modules [3].

These studies established the feasibility of using PCM as a passive thermal-management technique for photovoltaic applications. The thermophysical properties of PCM strongly influence its thermal-management capability. Important parameters include melting temperature, latent heat, thermal conductivity, density, specific heat and PCM quantity. A PCM with high latent heat can store a considerable amount of thermal energy; however, the relatively low thermal conductivity of many paraffin-based PCMs can restrict the rate of heat transfer from the PV module to the PCM.

Hasan et al. investigated the characterization of PCM materials for photovoltaic thermal control and emphasized that the phase-transition temperature should be compatible with the operating temperature range of the PV module [4]. Hasan et al. also demonstrated that PCM-based temperature regulation can improve PV performance and energy generation under suitable operating conditions [5]. The limitation of low PCM thermal conductivity has motivated the development of thermal-conductivity enhancement techniques. Conductive materials such as graphite and metallic structures have been investigated to improve heat transfer within PCM systems. Maiti et al. investigated a metal–wax composite phase-change matrix for self-regulation of photovoltaic module temperature and demonstrated that the incorporation of conductive metallic material can improve thermal regulation [6]. Biwole et al. also investigated the application of PCM for improving solar-panel performance and demonstrated that PCM can delay the temperature rise of PV panels [7]. Metallic fins are particularly attractive for PV applications because of their high thermal conductivity, simple geometry and ease of integration with PCM containers. Aluminium fins can provide conductive pathways from the rear surface of the PV module into the PCM and distribute the absorbed thermal energy over a larger PCM volume. Atkin and Farid experimentally investigated a PV thermal-management system using PCM-infused graphite and an aluminium finned heat sink. Their results demonstrated that combining latent-heat storage with conductive heat-transfer enhancement can improve PV thermal management compared with individual approaches [8].

The effect of PV temperature on electrical performance has also been extensively investigated. Dubey et al. reviewed the temperature dependence of photovoltaic efficiency and reported that increasing PV temperature generally results in a reduction in electrical conversion efficiency [9]. Therefore, reducing the operating temperature of PV modules using PCM and fin-assisted thermal management has the potential to increase electrical power and energy generation. Hasan et al. investigated the energy and cost implications of PV–PCM systems and reported that temperature regulation can contribute to improved PV performance, although the economic benefit depends on the additional system cost and resulting energy gain [5]. Several review studies have summarized the development of PCM-assisted photovoltaic thermal management. Ma et al. reviewed the use of PCMs in photovoltaic systems for thermal regulation and electrical-efficiency improvement and identified PCM selection, thermal conductivity, system configuration and heat-transfer enhancement as important parameters [10]. Browne et al. reviewed PCM applications for photovoltaic thermal management and emphasized the importance of PCM melting behaviour and heat-transfer characteristics [11]. Hasan et al. compared different PCM materials under different climatic conditions and demonstrated that the suitability of a PCM depends on the operating climate and temperature range of the PV module [12].

Islam et al. reviewed advances in photovoltaic–PCM technology and highlighted heat-transfer enhancement as an important research area for overcoming the low thermal conductivity of PCMs [13]. Hasanuzzaman et al. reviewed different PV cooling technologies and identified PCM as an attractive passive cooling technique because it can reduce PV operating temperature without continuous auxiliary power consumption [14]. These review studies demonstrate the potential of PCM-based thermal management while also identifying thermal conductivity and system configuration as continuing challenges.The heat-transfer behaviour of PV–PCM systems is affected by both environmental and geometrical conditions. Kant et al. investigated heat transfer in photovoltaic panels coupled with PCM and demonstrated that factors such as natural convection within molten PCM, wind velocity and panel inclination can influence thermal behaviour [15].

Shukla et al. reviewed different PV cooling methodologies and emphasized the importance of reducing PV operating temperature to improve electrical efficiency [16]. Hachem et al. experimentally investigated pure and combined PCMs for improving photovoltaic performance and demonstrated that PCM composition and operating conditions influence the resulting thermal and electrical performance [17].

Fin geometry is an important consideration in the design of PCM-assisted PV thermal-management systems. Increasing the number of fins can provide additional conductive pathways and increase the effective heat-transfer area. However, excessive fin density can reduce the available PCM volume for latent-heat storage. Consequently, fin spacing represents a compromise between conductive heat-transfer enhancement and PCM storage volume. Closely spaced fins can improve heat spreading from the PV rear surface, whereas widely spaced fins provide more PCM volume but may increase the thermal resistance through the PCM. Khanna et al. investigated the performance of tilted photovoltaic systems integrated with PCM under varying operating conditions and demonstrated that PCM can reduce PV temperature and improve electrical efficiency [18]. Their subsequent work investigated the optimization of finned PV–PCM systems and demonstrated that fin dimensions and configuration influence the thermal performance of the system [19]. These findings are particularly relevant to the present study because they establish fin geometry as an important design variable in fin-assisted PV–PCM systems.

Although previous research has established the effectiveness of PCM and conductive fins for photovoltaic thermal management, direct comparison of different fin spacings under controlled experimental conditions remains limited. Differences in PV module dimensions, PCM mass, fin dimensions, environmental conditions and measurement procedures make direct comparison between published studies difficult. In particular, systematic experimental investigation of aluminium-fin spacing while maintaining the PCM material, PCM mass, fin material and fin dimensions constant is required.

Therefore, the present study focuses specifically on the influence of aluminium-fin spacing in a PCM-assisted photovoltaic thermal-management system. Three fin spacings of 10, 20 and 30 mm are investigated while maintaining the major experimental parameters constant.

The thermal and electrical performance is evaluated using PV temperature, PCM temperature, solar irradiance, voltage, current, electrical power, conversion efficiency and cumulative energy generation. This controlled experimental approach enables the specific influence of fin spacing on heat transfer and PV electrical performance to be evaluated.

Overall, the previous literature establishes that PCM can provide effective passive thermal regulation for photovoltaic modules and that conductive fins can improve heat transfer within PCM systems [8,19]. However, the interaction between fin spacing, PCM utilization, PV temperature reduction and electrical performance require further experimental investigation. The present study addresses this research gap by systematically comparing 10, 20 and 30 mm aluminium-fin spacing under variable outdoor solar conditions.

3.RESEARCH GAP

The existing literature demonstrates that PCM integration can provide passive thermal regulation for photovoltaic modules. However, the relatively low thermal conductivity of many PCMs can restrict heat transfer and delay effective utilization of the PCM latent heat capacity. Heat-transfer enhancement using metallic fins has therefore emerged as an important approach for improving PCM performance.

Despite significant research on PV–PCM systems, further experimental investigation is required to establish the combined thermal and electrical influence of PCM and aluminium fins under variable outdoor solar conditions. In particular, a direct experimental comparison between a conventional PV module, a PCM-integrated module and a PCM–finned module can provide useful information regarding the contribution of the fin structure. The present study is that the experimental evaluation of the thermal and electrical performance of a fin-enhanced PCM system under varying solar irradiance, with simultaneous comparison against conventional PV and PCM-only configurations. The study focuses on experimentally measurable parameters including PV temperature, PCM temperature, solar irradiance, voltage, current, electrical power and conversion efficiency.

4.EXPERIMENTAL CONCEPT

This figure 1 illustrates the three PV configurations used in the study: conventional PV (PV-0), PV with PCM and PV with PCM and aluminium fins. For the fin-assisted configuration, three fin spacings—10 mm, 20 mm and 30 mm are investigated while keeping the other experimental parameters constant. This allows the effect of fin spacing on PV thermal and electrical performance to be evaluated.

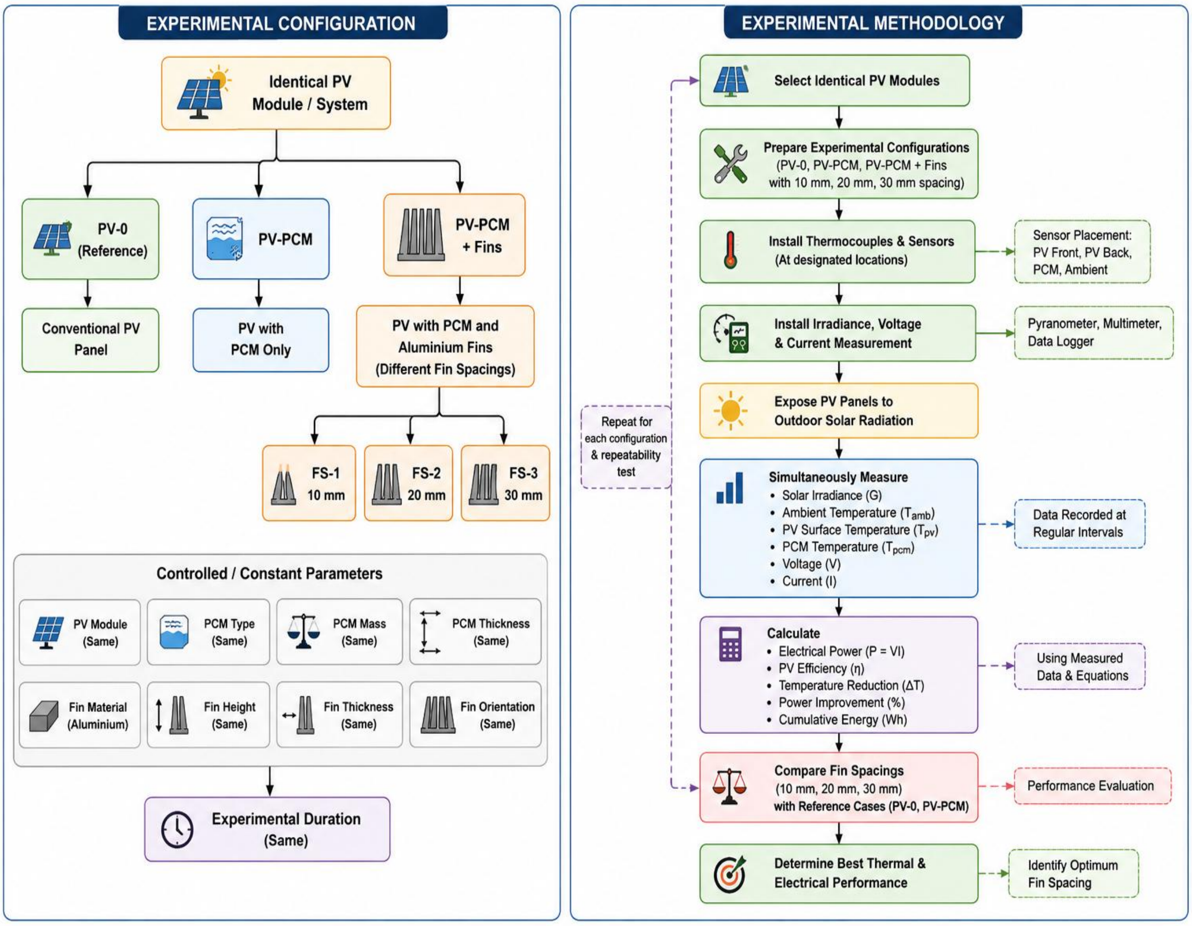

Figure 1. Schematic representation of the experimental configurations.

This figure 2 represents the sequence of the experimental procedure, starting with the preparation of identical PV modules and installation of sensors, followed by outdoor solar testing and simultaneous measurement of solar irradiance, temperature, voltage and current. The measured data are then used to calculate power, efficiency, temperature reduction and energy generation, enabling comparison of the different fin spacings and identification of the optimum configuration.

The flow chart of the experimental methodology for PV–PCM thermal management illustrates the systematic procedure followed to evaluate the thermal and electrical performance of the proposed photovoltaic system. The experiment begins by installing the reference and test PV modules under identical orientation and inclination, followed by the installation of temperature sensors and the attachment of the PCM container to the rear surface of the test panel. Aluminium fins are then installed at the selected spacings and the predetermined quantity of PCM is filled and sealed inside the container. After verifying the electrical connections and recording the initial temperatures, solar irradiance, ambient temperature, PV temperature, PCM temperature, voltage and current are measured simultaneously throughout the test period. The experiment is repeated for each fin spacing and selected tests are repeated to assess experimental repeatability.

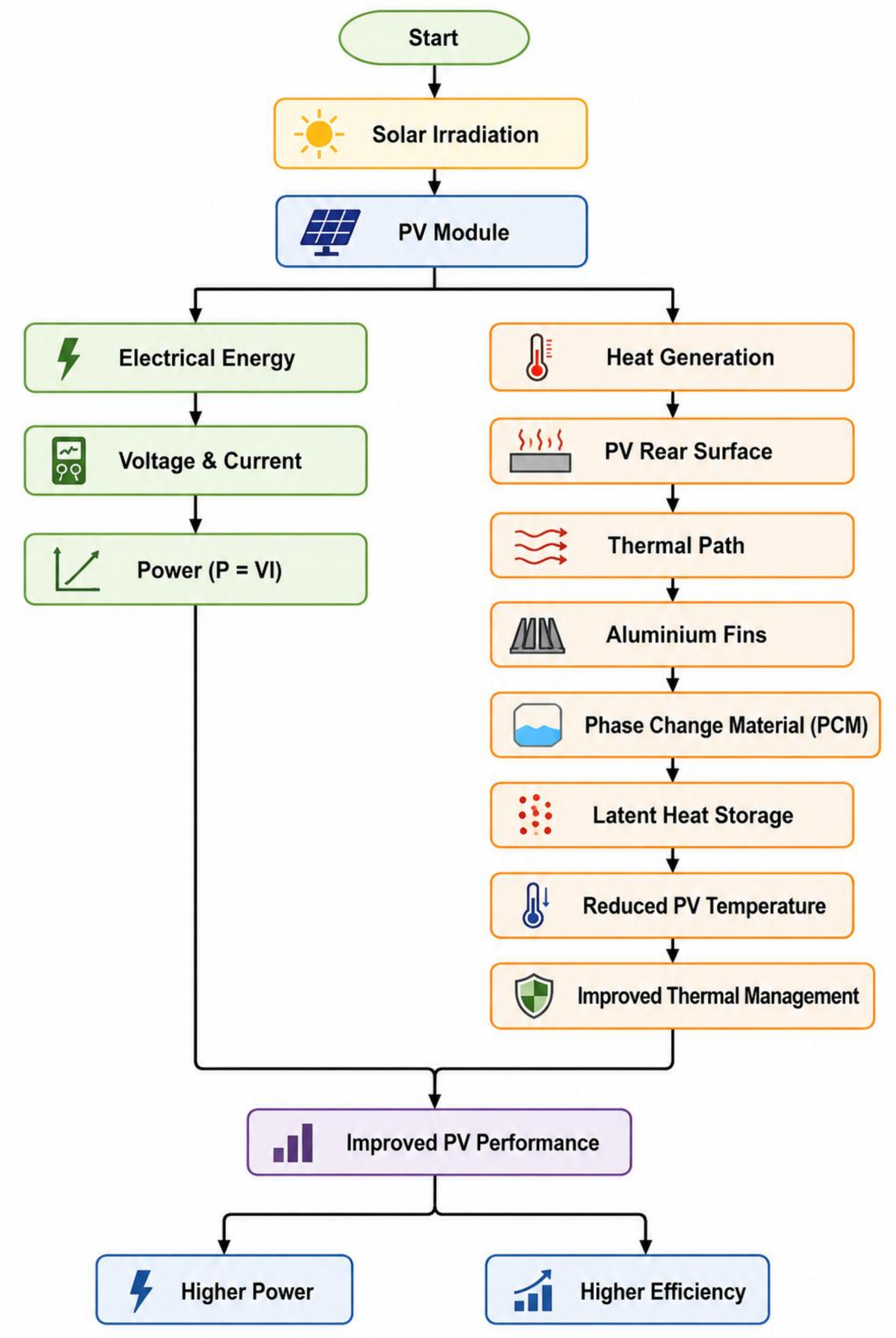

Figure 2. Flow chart of the experimental methodology for PV–PCM thermal management.

4.1 Experimental Procedure

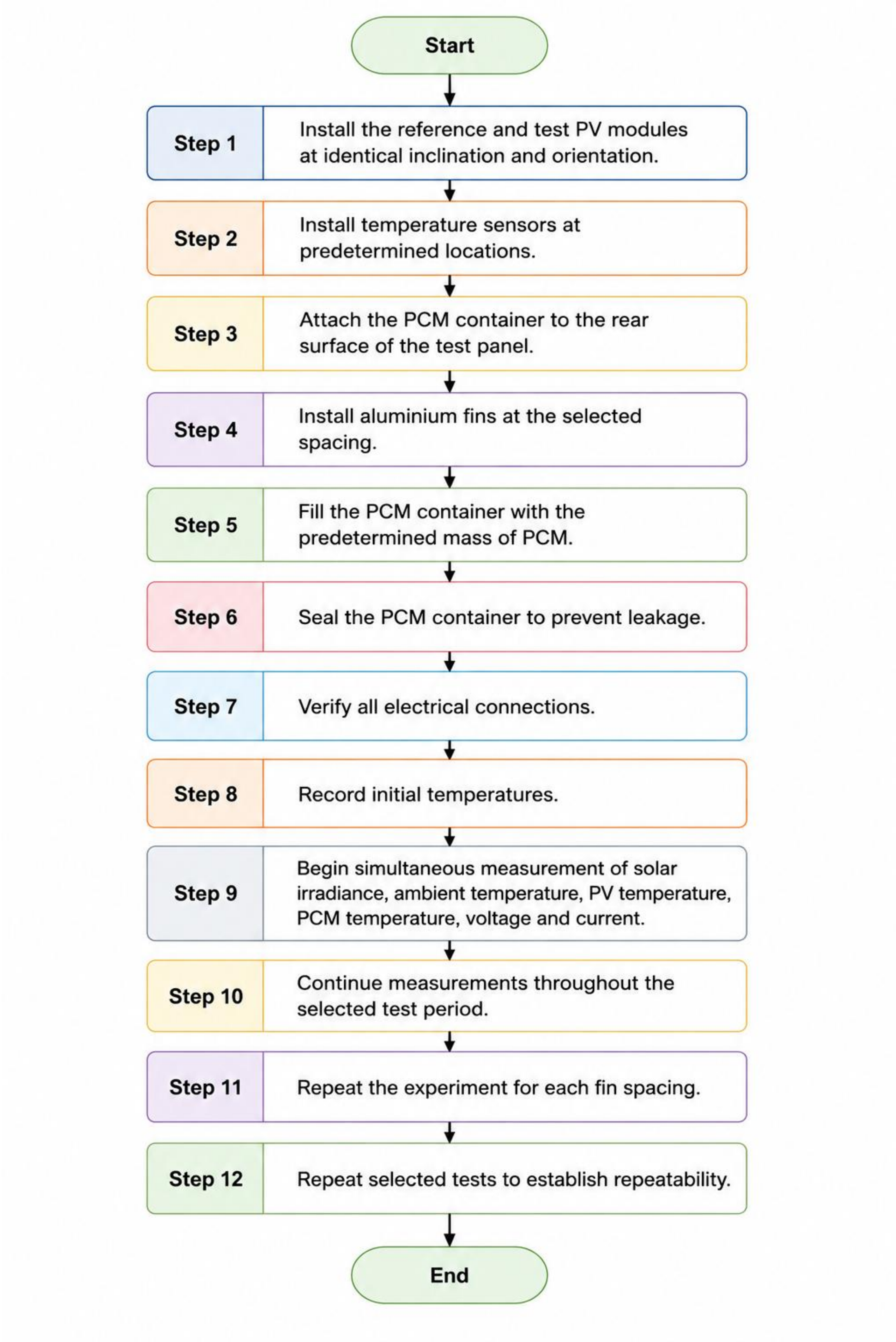

Figure 3. Detailed experimental procedure

The experiments were conducted under outdoor solar conditions to evaluate the thermal and electrical performance of the PV module with PCM and aluminium fins. Five configurations were tested: bare PV, PCM-integrated PV and PCM-integrated PV with aluminium fins at 10, 20 and 30 mm spacing. During each test, solar irradiance, PV temperature, PCM temperature, voltage and current were measured at regular time intervals. The recorded data were used to determine electrical power, conversion efficiency and cumulative energy generation. The results obtained from the different configurations were then compared to assess the effect of fin spacing on PV thermal regulation and electrical performance.

Figure 3 illustrates the detailed experimental procedure followed for evaluating the PCM-assisted PV thermal-management system. The procedure includes the preparation of the different PV configurations, outdoor exposure under solar radiation, measurement of PV and PCM temperatures, recording of solar irradiance and electrical parameters and subsequent calculation of power, efficiency and cumulative energy generation. The same procedure was followed for all configurations to ensure a consistent comparison of the effect of aluminium-fin spacing.

4.2 Experimental Approach

4.2.1 Experimental concept and configurations

The experimental investigation was designed to evaluate the influence of aluminium-fin spacing on the thermal and electrical performance of a photovoltaic (PV) module integrated with a paraffin-based phase change material (PCM). A conventional PV module was used as the reference configuration (PV Reference), while PCM-assisted configurations were evaluated with aluminium fins. Three fin spacings 10, 20 and 30 mm were investigated. The PV module characteristics, PCM type and mass, fin material and fin dimensions were maintained constant so that fin spacing remained the principal independent variable. The experimental arrangement consisted of the PV module, a PCM container attached to the rear surface of the module and aluminium fins installed within the PCM region. The fins provide conductive pathways from the PV rear surface into the PCM, thereby increasing the effective heat-transfer area and distributing heat over a larger PCM volume. The thermal-management mechanism therefore combines the high thermal conductivity of aluminium with the latent-heat storage capability of the PCM.

4.2.2 PV module and PCM specifications

Parameter	Value
PV technology	Monocrystalline
Rated power	100 W
Maximum power voltage	18.0 V
Maximum power current	5.56 A
Open-circuit voltage	22.5 V
Short-circuit current	5.90 A
Dimensions	1000 × 650 mm
Active area	0.65 m²
Temperature coefficient	−0.40 %/°C

Table 1: PV module and PCM specifications

The PCM was a paraffin-based material with a melting temperature of 42 °C, latent heat of 170 kJ/kg, thermal conductivity of 0.20 W/m·K, density of 880 kg/m³, specific heat of 2.0 kJ/kg·K and a total PCM mass of 8 kg.

4.2.3 Aluminium-fin configurations

Parameter	Value
Fin material	Aluminium
Fin thickness	2 mm
Fin height	40 mm
Fin length	650 mm
Fin spacing	10 / 20 / 30 mm
Number of fins	22 / 15 / 10
Fin conductivity	205 W/m·K

Table 2: Aluminium-fin configurations

4.2.4 Measurement and experimental procedure

Identical PV modules were installed under the same orientation and inclination. Temperature sensors were installed to monitor the PV surface and PCM and the PCM container was attached to the rear surface of the test module. For the fin-assisted cases, aluminium fins were installed at the prescribed spacing and the predetermined PCM quantity was filled and sealed in the container. Electrical connections were checked before testing and initial temperatures were recorded.

Outdoor testing was then conducted under variable solar irradiance. Solar irradiance, ambient temperature, PV temperature, PCM temperature, voltage and current were measured simultaneously at 1-min intervals. The experiment was repeated for each fin spacing and selected tests were intended to be repeated to assess experimental repeatability. The measurement accuracies reported in the study were ±5 W/m² for irradiance, ±0.5 °C for PV and PCM temperature, ±0.5 °C for ambient temperature, ±0.1 V for voltage and ±0.05 A for current.

4.2.5 Data reduction and performance parameters

Electrical power was calculated from the measured voltage and current as:

P = V I ----------(eqn.1)

PV conversion efficiency was calculated from the electrical output relative to the incident solar power on the active module area. Cumulative energy generation was obtained by integrating the electrical power over the experimental duration. The performance assessment considered maximum PV temperature, average PV temperature, temperature reduction, maximum and average power, conversion efficiency and cumulative energy generation.

Because outdoor irradiance varies continuously, thermal and electrical results should be interpreted together with the corresponding irradiance history. The study identifies sensible heating, phase-transition and post-melting behaviour from the PCM temperature response.

5. RESULTS AND DISCUSSION

5.1 Overall thermal and electrical performance

The reported performance data show a clear improvement with the incorporation of PCM and aluminium fins compared with the conventional PV reference. The reference panel reached a maximum temperature of 61.0 °C and an average temperature of 52.8 °C. With PCM integration, these values decreased to 53.0 °C and 46.7 °C respectively, corresponding to a temperature reduction of 8.0 °C. This indicates that the PCM effectively absorbed part of the excess heat generated by the PV module during operation. Further improvement was observed with the addition of aluminium fins. The 10 mm fin-spacing configuration (FS-1) achieved the lowest maximum temperature of 49.0 °C and average temperature of 43.8 °C, resulting in the highest reported temperature reduction of 12.0 °C compared with the reference panel. The improved performance can be attributed to the closer fin arrangement, which provides additional conductive pathways for transferring heat from the PV module to the PCM. The lower average temperature also indicates improved thermal regulation throughout the test period. These results confirm that the combination of PCM and aluminium fins is more effective than PCM alone, with the 10 mm fin spacing providing the best thermal performance among the tested configurations.

5.2 Effect of fin spacing on PV temperature

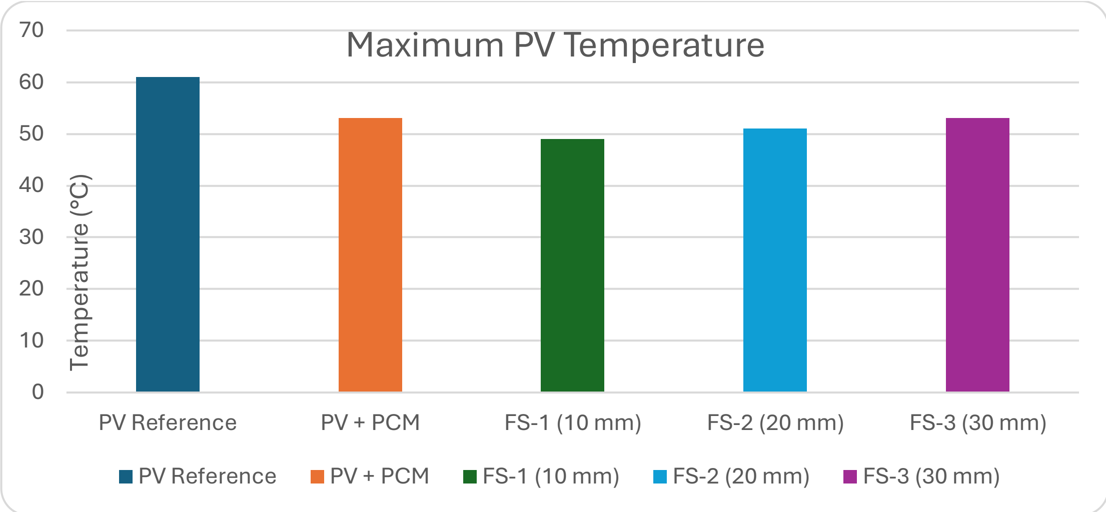

Figure 4. Graph between different configuration and Max.Temperature

Figure 4 illustrates spacing had a clear influence on the reported thermal response. The 10 mm configuration (FS-1) provided the strongest thermal reduction, followed by the 20 mm configuration (FS-2) and the 30 mm configuration (FS-3). Maximum PV temperature decreased from 61.0 °C for the reference panel to 49.0 °C for FS-1, representing a 12.0 °C reduction. The corresponding average temperature decreased from 52.8 °C to 43.8 °C. FS-2 and FS-3 showed maximum temperatures of 51.0 °C and 53.0 °C respectively.

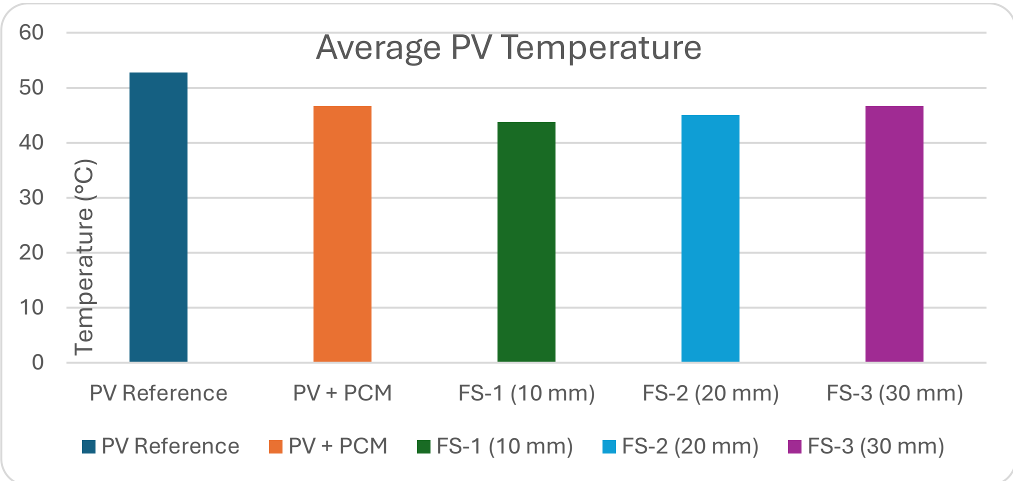

Figure 5. Graph between different configuration and Max.Temperature

Figure 5 explains stronger thermal performance at 10 mm spacing is consistent with the proposed heat-transfer mechanism: a greater number of aluminium fins provides more conductive pathways and distributes heat more effectively into the PCM. However, the result should not be interpreted as evidence that progressively smaller spacing will always be superior, because excessive fin density can reduce the PCM volume available for latent-heat storage. The optimum design therefore depends on the combined thermal response, electrical output, PCM utilization and practical fabrication considerations.

5.3 PCM thermal behaviour

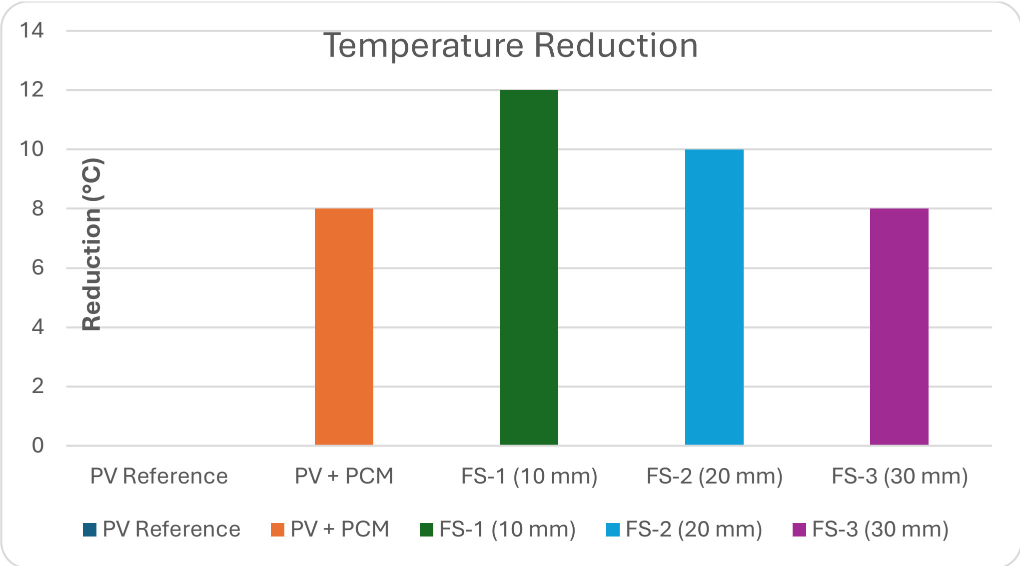

Figure 6. Graph between different configuration and Temperature Reduction

Figure 6 illustrates PCM temperature response is intended to distinguish sensible heating, the phase-transition period around the 42 °C melting temperature and post-melting heating. During phase transition, latent heat absorption can limit the rate of temperature increase. Aluminium fins are expected to enhance conductive heat distribution within the PCM and thereby improve the utilization of the available PCM volume. The supplied study specifies the PCM properties and measurement method but does not provide the complete time-resolved PCM temperature data; consequently, specific melting times or phase-transition durations cannot be reported from the available material.

5.4 Electrical power and efficiency

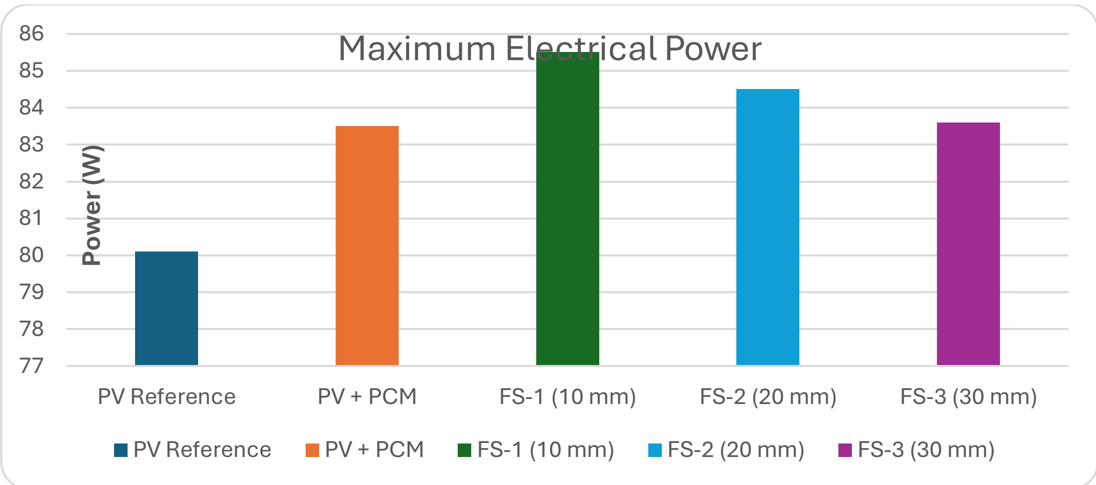

Figure 7. Graph between different configuration and Max. Electrical Power

Figure 7 explains the electrical results follow the thermal trend. Maximum power increased from 80.1 W for the conventional reference to 83.5 W for PV + PCM and 85.5 W for FS-1. The average power increased from 68.6 W for the reference to 70.9 W for PV + PCM and 72.2 W for FS-1. FS-2 and FS-3 produced average powers of 71.7 W and 71.0 W respectively. These values indicate that the 10 mm fin spacing provided the highest reported electrical output among the tested configurations.

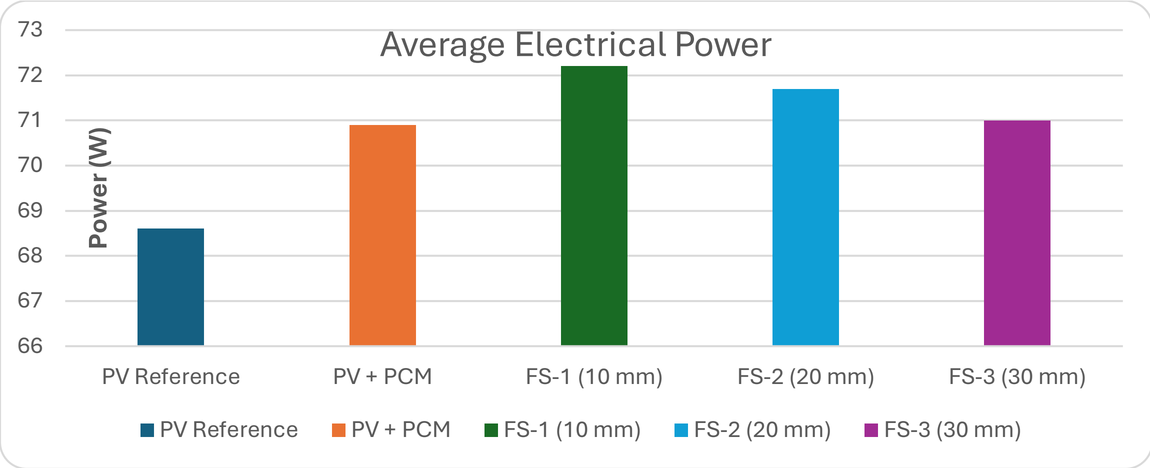

Figure 8. Graph between different configuration and Avg. Electrical Power

Figure 8 illustrates reported conversion efficiency was 14.17% for the reference panel, increasing to 14.65% for PV + PCM, 14.91% for FS-1, 14.80% for FS-2 and 14.67% for FS-3. Relative to the reference, the reported efficiency increase for FS-1 is 0.74 percentage points or approximately 5.2% on a relative basis. The increase in electrical performance is consistent with the lower PV operating temperature; however, because irradiance and electrical operating conditions influence output, the comparison should be interpreted using the measured irradiance conditions rather than temperature alone.

5.5 Cumulative energy generation

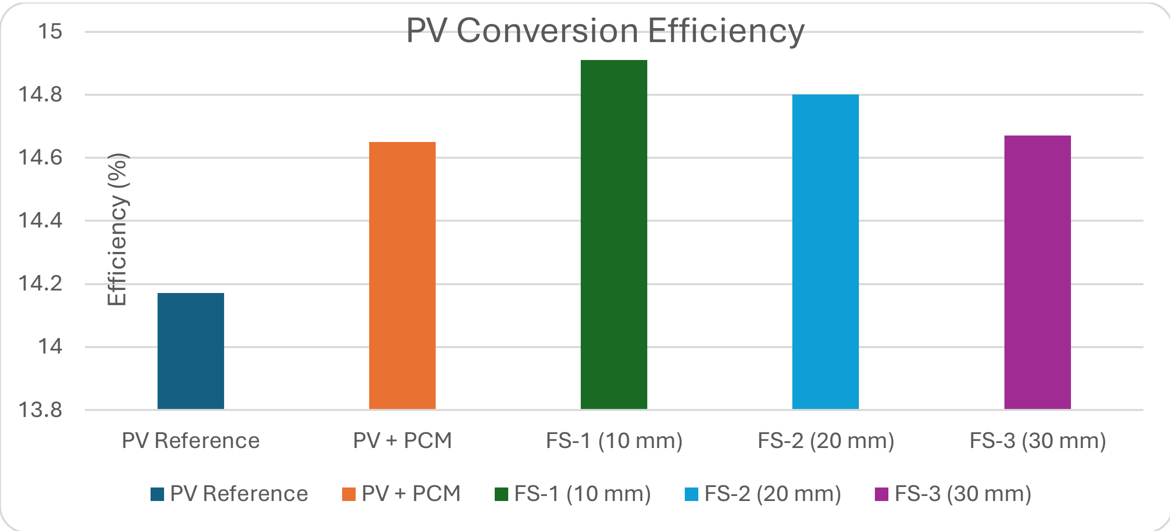

Figure 9. Graph between different configuration and Conversion Efficiency

Figure 9 shows conversion efficiency by different fin spacing. cumulative energy-generation results further demonstrate the benefit of incorporating thermal-management techniques into the PV system. The reference PV panel generated 411.7 Wh during the experimental period, while the PV + PCM configuration increased the energy generation to 425.7 Wh, indicating that PCM-based thermal regulation can improve the electrical output by reducing the operating temperature of the PV module. Among the fin-assisted configurations, FS-1 (10 mm fin spacing) achieved the highest cumulative energy generation of 433.2 Wh, followed by FS-2 (20 mm) at 430.1 Wh and FS-3 (30 mm) at 426.1 Wh. Compared with the reference panel, FS-1 produced an additional 21.5 Wh of electrical energy, corresponding to an improvement of approximately 5.2%. The higher energy generation obtained with FS-1 can be attributed to the closer fin spacing, which provides more conductive pathways for transferring heat from the PV module to the PCM and thereby supports better thermal regulation. The reduction in energy generation with increasing fin spacing from 10 to 30 mm indicates that fin arrangement influences the effectiveness of heat transfer and PCM utilization. Overall, the results demonstrate that appropriate fin spacing can enhance the thermal-management capability of the PCM system and consequently improve the cumulative electrical energy output of the PV module.

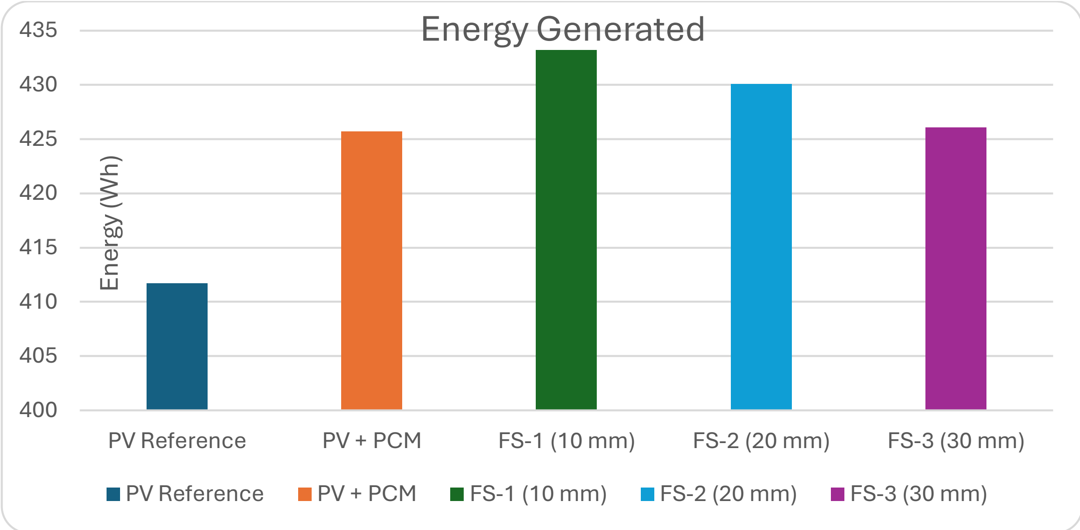

Figure 10. Graph between different configuration and Energy generated

Figure 10 shows the energy generated by the different PV configurations. The results indicate that the PCM and aluminium fin-assisted configurations generate more energy than the conventional PV panel, mainly due to improved temperature control and better PV performance.

5.6 Comparative performance and optimum fin spacing

Parameter	PV Reference	PV + PCM	FS-1 (10 mm)	FS-2 (20 mm)	FS-3 (30 mm)
Max. temperature (°C)	61.0	53.0	49.0	51.0	53.0
Average temperature (°C)	52.8	46.7	43.8	45.0	46.7
Temperature reduction (°C)	—	8.0	12.0	10.0	8.0
Maximum power (W)	80.1	83.5	85.5	84.5	83.6
Average power (W)	68.6	70.9	72.2	71.7	71.0
Efficiency (%)	14.17	14.65	14.91	14.8	14.67
Energy generated (Wh)	411.7	425.7	433.2	430.1	426.1

Table 3: Comparative performance and optimum fin spacing

Table 3 illustrates the reported maximum and average PV temperatures, power, efficiency and energy generation together, FS-1 (10 mm) provides the best overall performance among the investigated configurations. It achieved the lowest maximum temperature, lowest average temperature, largest temperature reduction, highest maximum power, highest average power, highest efficiency and highest reported energy generation. The 10 mm spacing can therefore be identified as the optimum configuration within the three spacings investigated. This conclusion is restricted to the tested configurations and should not be generalized to fin spacings outside the experimental range without additional measurements.

5.7 Uncertainty, repeatability and limitations

The reported instrument accuracies indicate that measurement uncertainty should be considered when interpreting the experimental differences. In particular, the uncertainty in electrical power depends on both voltage and current measurements, while efficiency uncertainty additionally depends on irradiance and active-area measurements. The supplied study recommends repeating each experimental condition at least three times where practical and reporting the mean and standard deviation. The available document does not provide replicate-level measurements or calculated standard deviations, so statistical uncertainty values are not added here.

The principal experimental limitations are the variable outdoor irradiance and wind conditions, the relatively low thermal conductivity of the PCM and the possibility of complete PCM melting during prolonged high-irradiance operation. Once a substantial portion of the latent-heat capacity is consumed, the thermal-regulation capability may decrease. Longer-duration and repeated outdoor tests would therefore be required to establish seasonal and long-term performance.

5.8 Discussion of thermal mechanism

The observed performance trend can be explained by the intended heat-transfer path from solar radiation to the PV module, then through the rear surface and aluminium fins into the PCM. The aluminium fins provide high-conductivity paths that spread heat through a greater PCM volume. When the PCM approaches its phase-transition range, latent heat absorption limits the rate of temperature increase. The combination of conductive heat spreading by aluminium and latent heat storage by the PCM consequently reduces the PV operating temperature and supports improved electrical performance.

6. CONCLUSIONS

An experimental methodology for investigating the influence of aluminium fin spacing on PCM-based thermal management of photovoltaic panels has been presented. The proposed approach combines the latent heat storage capability of PCM with the enhanced heat-transfer capability of aluminium fins.

The principal experimental variable is fin spacing, while the PV module, PCM type, PCM mass, fin material, fin dimensions and operating orientation are maintained constant. This controlled approach enables the influence of fin spacing on PV temperature and electrical performance to be isolated. Solar irradiance, ambient temperature, PV temperature, PCM temperature, voltage and current are measured simultaneously. Electrical power, conversion efficiency, temperature reduction and cumulative energy generation are calculated from the experimental measurements.

The expected advantage of the fin-assisted configuration is improved heat distribution from the PV module into the PCM. However, the optimum fin spacing cannot be established theoretically alone and should be determined from the experimental results. The proposed study provides a practical experimental methodology for improving PV thermal management without continuous auxiliary cooling power. The experimentally obtained results can also provide a foundation for subsequent optimization of PCM mass and fin geometry.

The final performance of the proposed system should be reported using the experimentally measured temperature reduction, power improvement and energy-generation data. No numerical performance claim should be made without experimental verification.

REFERENCE

[1] Waqas, A., Kumar, S. and others, "Thermal and electrical management of photovoltaic panels using phase change materials: A review," *Renewable and Sustainable Energy Reviews*, [verify exact volume, pages and DOI before submission].

[2] Huang, M. J., Eames, P. C. and Norton, B., "Phase change materials for limiting temperature rise in building integrated photovoltaics," *Solar Energy*, vol. 80, no. 9, pp. 1121–1130, 2006. doi:10.1016/j.solener.2005.10.006.

[3] Hasan, A., McCormack, S. J., Huang, M. J. and Norton, B., “Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics,” *Solar Energy*, vol. 84, no. 9, pp. 1601–1612, 2010. doi:10.1016/j.solener.2010.06.010.

[4] Hasan, A., McCormack, S. J., Huang, M. J. and Norton, B., “Characterization of phase change materials for thermal control of photovoltaics using Differential Scanning Calorimetry and Temperature History Method,” *Energy Conversion and Management*, vol. 81, pp. 322–329, 2014. doi:10.1016/j.enconman.2014.02.042.

[5] Biwole, P. H., Eclache, P. and Kuznik, F., “Phase-change materials to improve solar panel's performance,” *Energy and Buildings*, vol. 62, pp. 59–67, 2013. doi:10.1016/j.enbuild.2013.02.059.

[6] Maiti, S., Banerjee, S., Vyas, K., Patel, P. and Ghosh, P. K., “Self regulation of photovoltaic module temperature in V-trough using a metal–wax composite phase change matrix,” *Solar Energy*, vol. 85, no. 9, pp. 1805–1816, 2011. doi:10.1016/j.solener.2011.04.021.

[7] Atkin, P. and Farid, M. M., “Improving the efficiency of photovoltaic cells using PCM infused graphite and aluminium fins,” *Solar Energy*, vol. 114, pp. 217–228, 2015. doi:10.1016/j.solener.2015.01.037.

[8] Ho, C. J., Tanuwijava, A. O. and Lai, C. M., “Thermal and electrical performance of a BIPV integrated with a microencapsulated phase change material layer,” *Energy and Buildings*, vol. 50, pp. 331–338, 2012. doi:10.1016/j.enbuild.2012.04.003.

[9] Dubey, S., Sarvaiya, J. N. and Seshadri, B., “Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world – A review,” *Energy Procedia*, vol. 33, pp. 311–321, 2013. doi:10.1016/j.egypro.2013.05.072.

[10] Hasan, A., McCormack, S. J., Huang, M. J. and Norton, B., “Energy and cost saving of a photovoltaic-phase change materials (PV-PCM) system through temperature regulation and performance enhancement of photovoltaics,” *Energies*, vol. 7, no. 3, pp. 1318–1331, 2014. doi:10.3390/en7031318.

[11] Ma, T., Yang, H., Zhang, Y., Lu, L. and Wang, X., “Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: A review and outlook,” *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 1273–1284, 2015. doi:10.1016/j.rser.2014.12.003.

[12] Browne, M. C., Norton, B. and McCormack, S. J., “Phase change materials for photovoltaic thermal management,” *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 762–782, 2015. doi:10.1016/j.rser.2015.03.050.

[13] Hasan, A., McCormack, S. J., Huang, M. J., Sarwar, J. and Norton, B., “Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates,” *Solar Energy*, vol. 115, pp. 264–276, 2015. doi:10.1016/j.solener.2015.02.003.

[14] Islam, M. M., Pandey, A. K., Hasanuzzaman, M. and Rahim, N. A., “Recent progresses and achievements in photovoltaic-phase change material technology: A review with special treatment on photovoltaic thermal-phase change material systems,” *Energy Conversion and Management*, vol. 126, pp. 177–204, 2016. doi:10.1016/j.enconman.2016.07.075.

[15] Hasanuzzaman, M., Malek, A. B. M. A., Islam, M. M., Pandey, A. K. and Rahim, N. A., “Global advancement of cooling technologies for PV systems: A review,” *Solar Energy*, vol. 137, pp. 25–45, 2016. doi:10.1016/j.solener.2016.07.010.

[16] Kant, K., Shukla, A., Sharma, A. and Biwole, P. H., “Heat transfer studies of photovoltaic panel coupled with phase change material,” *Solar Energy*, vol. 140, pp. 151–161, 2016. doi:10.1016/j.solener.2016.11.006.

[17] Shukla, A., Kant, K., Sharma, A. and Biwole, P., “Cooling methodologies of photovoltaic module for enhancing electrical efficiency: A review,” *Solar Energy Materials and Solar Cells*, vol. 160, pp. 275–286, 2017. doi:10.1016/j.solmat.2016.10.047.

[18] Hachem, F., Abdulhay, B., Ramadan, M., El Hage, H., El Rab, M. G. and Khaled, M., “Improving the performance of photovoltaic cells using pure and combined phase change materials – Experiments and transient energy balance,” *Renewable Energy*, vol. 107, pp. 567–575, 2017. doi:10.1016/j.renene.2017.02.032.

[19] Khanna, S., Reddy, K. S. and Mallick, T. K., “Performance analysis of tilted photovoltaic system integrated with phase change material under varying operating conditions,” *Energy*, vol. 133, pp. 887–899, 2017. doi:10.1016/j.energy.2017.05.150.

[20] Khanna, S., Reddy, K. S. and Mallick, T. K., “Optimization of finned solar photovoltaic phase change material (finned PV PCM) system,” *International Journal of Thermal Sciences*, vol. 130, pp. 313–322, 2018. doi:10.1016/j.ijthermalsci.2018.04.033.