

AN INVENTIVE COOLING METHOD FOR FLOATING SOLAR PV PANELS: UTILIZING PHASE CHANGE MATERIAL IN MIZORAM, INDIA

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Abstract

Water shortage and energy scarcity are two global issues that require cooperation. Consequently, the global popularity of floating photovoltaic solar (FPV) systems, installed on the water's surface, is increasing. A solar panel experiences two primary effects when its temperature rises: thermal degradation and a significant reduction in output power. It significantly reduces the panel's longevity. Power losses and long-lasting thermal damage are encouraged by an uneven distribution of operating temperatures and, consequently, heat spots. To address such problems, an FPV panel, which is an electronic power generator, needs to remove heat from its surfaces quickly. To increase performance and decrease thermal heat loss from an FPV, the current study uses paraffin wax as a phase change material (PCM) that is mixed with graphene. To remove extra heat from FPV using water and improve overall performance, the suggested cooling solution was experimentally investigated at different tilt angles and climates in outdoor settings in Aizawl, Mizoram, India. This is accomplished by analysing the thermal and electrical performance of the FPV and PCM-FPV at different module tilt angles (12°, 18°, 24°, and 30°). In comparison to the baseline FPV system, the PCM-FPV Cooling system reduced the backside temperature by 8.77°C, resulting in an 18% increase in thermal regulation. Also, it was shown that using novel cooling technology (NCT) was significantly more efficient, with 13.55% more productivity and 5 m/s wind in a 57° direction. The NCT produces 9.15 kWh annually and more than 220 kWh over a 25-year operating lifespan.

Keywords: Renewable Energy; Solar PV; Floating Solar Photovoltaic systems; Power enhancement; Cooling technology; Phase change materials

Introduction

On Earth, these two resources interact either negatively or positively. Water and energy resources have become inseparable in recent decades. The process of producing electricity depends heavily on water resources. Conversely,

sources of energy are utilised for wastewater treatment, production of freshwater, transportation, and movement (Shokri and Fard, 2023). One viable strategy for resolving water scarcity concerns is to reduce water loss through surface evaporation. In

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lakes, canals, and natural water reservoirs, surface evaporation plays a major role in unprotected water loss. Different covers on the water have recently identified as a method for reducing surface evaporation (Cazzaniga *et al.*, 2018). The superiority of water-based floating photovoltaic systems over land-based ones in accomplishing goals like energy sources that don't emit carbon, superior performance rates, protecting limited resources, and conserving land has made them a far more competitive option (Sadati *et al.*, 2020). In countries with high population densities, where land scarcity drives up acquisition costs and makes land-mounted solar installations less economically viable, the FPV is an alluring substitute (Campana *et al.*, 2019). Floating photovoltaics (FPV) is anticipated to gain prominence and importance in the agriculture and hydropower sectors in both organic and artificial bodies of water globally as a rival to land-based LSPV (Banerjee *et al.*, 2025). The findings demonstrated that, in comparison to identical LSPV modules, the front and back temperatures of FPV modules were 2-4% and 5-11% lower, respectively. Nevertheless, other installation methods demonstrated significant promise in reducing the temperature of the PV module (Arenandan *et al.*, 2022). The cooling effect of floating FPV systems lowers the temperature of the FPV modules because they are positioned on the water's surface, enhancing energy production. Additionally, it was discovered that this technique, when combined with existing water reservoirs, improves the quality of the water, reduces the growth of algae, saves area of land for residential or farming use, and lowers shading, grid connection expenses, and water evaporation (Chirwa *et al.*, 2023). For a given amount of sunshine, raising the operating temperature significantly lowers power generation from PV cells by causing a slight increase in current, but considerable voltage decreases, as seen in Figure 1. It was discovered that the photovoltaic module's electrical efficiency decreased by 0.5% for every °C that the operating temperature rose.

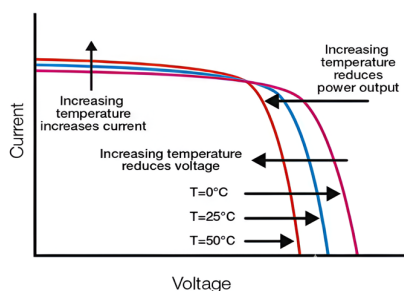


Figure 1. Temperature effects on output voltage and current profiles (Mankani *et al.*, 2022)

Using innovative lapping longitudinal plate fins as a passive cooling technique, (Elbreki *et al.*, 2021) examined the performance of a solar module. According to their experimental results, there was an approximate 10.69% increase in electricity efficiency. Additionally, it was determined that one of the key factors affecting the best cooling performance is the ambient microclimate. Commercial PCM RT27, which are packaged in plastic bags and fastened to the rear surface of the PV panel using wire mesh, are used in both numerical and experimental studies of the PV-PCM system. The trials' findings indicate that improved heat contact is required and that the PCM's melting point is too low, which prevents solidification on hot summer evenings. The electrical and thermal energy efficiency of the PV panel was experimentally investigated in relation to the addition of an RT42 PCM layer to the backside. They discovered that the temperature drop at the front and rear surfaces of PV was 12.3°C and 22.6°C, respectively, when integrated PCM and photovoltaics were used in the building, as opposed to PV without PCM. Furthermore, the implementation of PCM increased PV power generation by 7.2% at peak and 5.5% at daily average values, respectively (Brano *et al.*, 2013). A particular kind of paraffin phase change material (PCM) was used by RT28HC, which achieved an energy efficiency of 12.2% and an annual efficiency of 7.3%. Organic phase change materials exhibit poor thermal conductivity, despite PCM having a sizable latent heat of fusion per unit volume. Heat transfer is improved by adding a material with a high thermal conductivity to compensate for the insufficient one (Stropanik and Stritih, 2016). (Abdelrahman *et al.*, 2019) employed nanoparticle-integrated RT-35 HC PCM. Phase change materials (PCM) experienced a 52.3% decrease in temperature upon the incorporation of nanoparticles. To improve thermal uniformity and increase the surface area for heat transfer, (Huang *et al.*, 2011) included metallic fins into the phase-changing material (PCM). Both theoretical and practical approaches were used to examine PCM performance for heat transmission. (Maghrabie *et al.*, 2023) investigated the technological and financial benefits of using BioPCM to boost PV panel power production. Experimentally investigated the overall FPV performance (Elminshawy *et al.*, 2024), two identical floating FPV and land-based LPV polycrystalline panels with the same capacity set coplanar to each other under the same outdoor conditions. (examined tilt angle 10°, 15°, 20°, and 30°). In Egypt, Mediterranean climates and identified the FPV module at a tilt angle of 20° was found to have the

highest efficiency, with a mean daily average of 14.08% and a maximum value of 15.52%. A numerical and optimization study used Solar PV panels using carbon fi-ber-enhanced phase change materials (PCMs), layer was optimized to 48.2 mm thickness at kuwait and identified the passively cooled system reduces the panel's maximum temperature from around 72.5°C to approximately 57°C, leading to a daily efficiency improvement of approximately 0.61 % and an enhancement of 4.6 W in daily electric power output (Al-Masri *et al.*, 2025). An experimental investigation to enhance the efficiency of solar photovoltaic (Banda *et al.*, 2026) identified that PV-NBPCM has reduced the maximum surface temperature by around 18.86 K, compared to the other PV panels. While the average electrical efficiency and power output of a PV-NBPCM were improved by 10.71% and 24.60%, respectively, compared to other proposed PV panels. CFD analysis with three types of PCMs-Paraffin-ZnO, Lauric Acid (organic), and Calcium Nitrate Tetrahydrate, $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ (inorganic)-combined at Indonesia (Prasetyo S *Det al.*, 2025) with two fin geometries (diamond and honeycomb) and indentified Paraffin-ZnO achieved the highest electrical efficiency of 12.62% in the diamond fin without a cavity. In comparison, $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ exhibited the best thermal efficiency of 11.01% in the diamond fin with cavity. Lauric Acid demonstrated moderate but stable performance with an average electrical efficiency of 12.31% and thermal efficiency of 7.04%.

The current work's novelty

Based on the literature review above, the authors think that extended paraffin wax PCM with graphene on the rear surfaces of FPV panels is a dependable choice for cooling a solar cell when longevity, ease of maintenance, economics, and the environment are taken into consideration. A comprehensive experimental study of a novel cooling technology (NCT) for controlling the operating temperature of an independent floating solar module (FPV) is displayed in this research. By allowing cooling with the water around it to lower the surface temperature of the module and boost output, the suggested architecture offers a workable solution for the FPV module's thermal control.

In order to compare how well the FPV module works with the suggested NCT to that of the PCM-FPV module and plain FPV panels, a case study was finally carried out. To do this, sets of the suggested NCT and an experimental floating configuration

were constructed and placed in a water tank to examine the electrical and thermal performance of an FPV module under various operating circumstances. The authors examine for the first time the impacts of wind and how well the FPV modules work overall under consideration at tilt angles of 12°, 18°, 24°, and 30°, motivated by the NCT's presence in water. The chosen tilt angles (12°, 18°, 24°, and 30°) were selected to represent a practical range commonly recommended for PV installations across tropical and subtropical regions, including the study location. These angles encompass both near-optimal values for maximising annual solar irradiance capture and slightly higher/lower deviations to evaluate performance sensitivity.

Methodology

An experimental prototype, located at the Department of Mechanical Engineering, National Institute of Technology Mizoram, Aizawl City, 23.73° North and 92.71° East, India, is constructed and used to study a recently developed cooling strategy for floating photovoltaic systems in outdoor conditions.

Following the installation of the suggested NCT system in a sizable water basin, performance parameters are recorded as part of the experiment to help determine its effectiveness. The analysis considers the estimated efficiency of each FPV panel, which is determined by its power, irradiance, and area. At first, set two solar PV panels in a Water tank, one is plane, and another is with PCM, then set the tilt angle of the stand, then set all the equipment and collect data from 9:30 to 3:30 pm.

Experimental setup

The experimental setup consists of a 1000-litre water tank, a water circulation system, two floating FPV panels, a specially constructed floating platform, and measuring apparatus. Two identical floating FPV modules were used in this study; one had PCM, and the third was a standard one that was not tested outside. In the present study, a typical solar-energy polycrystalline Si-based PV module with a 10 W rated output and the appropriate setup were employed, with the technical details listed in Table 1. Figure 2 (a) displays both front and back perspectives of the conceptual architecture with equipment for the PCM-FPV and FPV plane systems used in this investigation, and (b) displays the overall schematic diagram during experimental time.

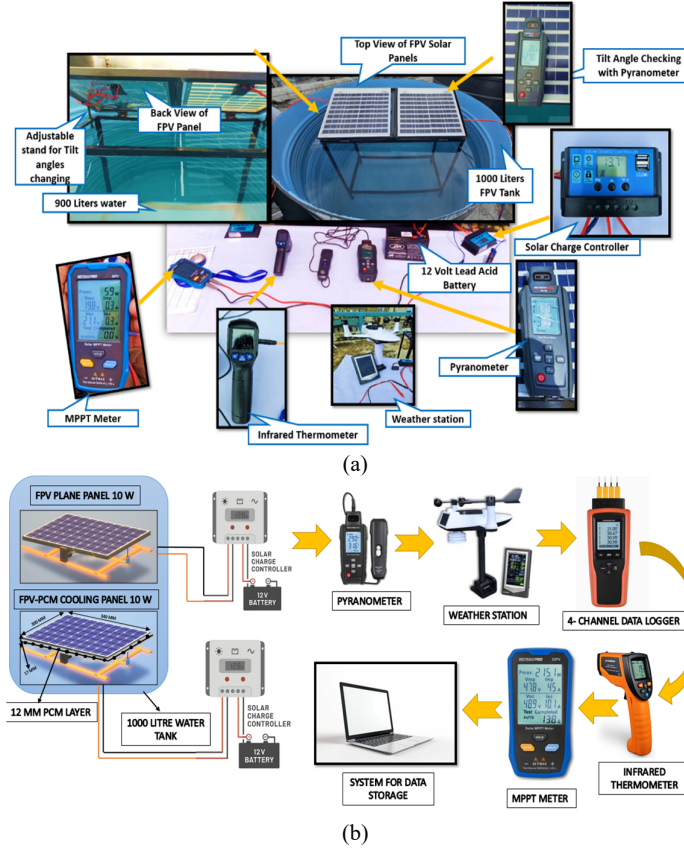


Figure 2. Temperature effects on output voltage and current profiles (Mankani *et al.*, 2022)

Table 1. Details regarding the used FPV Solar Panel specifications

Specification	Capacity
Power rating (P_{max})	10 Wp
Voltage rating (V_{mp})	18.0 V
Current rating (I_{mp})	0.55 A
Open Circuit voltage (V_{oc})	22.0 V
Short circuit current (I_{sc})	0.58 A
Panel Dimension	300×340×17 mm

At the water tank's top for testing, the FPV modules under examination were firmly fixed on an adjustable structure. To avoid long-term rust and corrosion, the entire construction is made of stainless steel; it is made up of two pieces that are 1.3 m long and 0.28 m in diameter on a stainless steel frame. A water tank of 106 cm by 72 cm by 166 cm was built to simulate a body of water, where the extended PCM-based FPV system is based on stainless steel structures.

Phase Change Material

The total performance of floating solar panels is enhanced by integrating FPV modules with

paraffin wax and graphene mixed PCM with an aluminium layer, which effectively regulates the panels' temperature. It can be written as follows, assuming that the PCM, or the amount of energy that the system maintains, is principally responsible for the energy held inside it, denoted Q_s , within the time Δt (in seconds). It can be expressed as follows in Figure 3.

$$Q_s = \begin{cases} m \cdot C_s (T_{PCM} - T_a) & \text{if } T_a < T_{PCM} < T_m \\ m \cdot C_s (T_m - T_a) + H & \text{if } T_{PCM} = T_m \\ m \cdot C_s (T_m - T_a) + H + m \cdot C_l (T_{PCM} - T_m) & \text{if } T_{PCM} > T_m \end{cases}$$

Figure 3. The calculation formula of PCM used in the FPV System

Where C_s and C_l represent the specific liquid and solid PCM temperatures, respectively, and are represented in joules per kilogram per Kelvin [J/(kg. K)]. Where m is the paraffin wax and graphene mixed PCM, expressed in kilograms (kg). T_m is the melting temperature in Kelvin, and H is the latent heat of fusion for PCM, measured in joules (J). The

characteristics of the used paraffin wax and graphene-mixed PCM are shown in Table 2.

Table 2. Characteristics of utilising metals and PCM

Name	Density (g/cm ³)	Thermal conductivity (W/m-K)	Heat capacity (J/mol-K)
Paraffin wax	0.83	0.15	206
Graphene	2.26	3000-5000	21-25
Aluminum	2.70	237	0.95

The backside of one of the SPV panels is made from paraffin wax and graphene mixed PCM that has been heated at 60°C to 65°C. After that, the PCM is compressed till it is around 12 mm thick. Figure 4 summarises the visual PCM production process. The reasoning behind the choice of a 12 mm PCM layer thickness has been provided. This thickness was optimised following preliminary trials that aimed to balance thermal storage capacity and structural integrity. Layers thicker than 15 mm caused slower heat dissipation and mechanical instability, while layers thinner than 10 mm failed to deliver sufficient cooling effects. Consequently, 12 mm was chosen as the best compromise for effective thermal management.

At first, mechanically grind or process the solid paraffin wax into fine powder to facilitate uniform melting and mixing. Then use a weighting machine to measured the precise amount of powdered paraffin wax required for the composite formulation, then heat the powdered PCM used a magnetic stirrer, Monitor the temperature with a thermometer until the wax reached its melting –

point (60-62°C) and transitions into a liquid state, add 4% graphene powder to the liquid PCM, (96% paraffin wax and 4% graphene), stir the mixture thorough used a magnetic stirrer to ensure homogeneous dispersion of graphene within the PCM matrix, pour the PCM-graphene mixture into a mold to form a uniform PCM layer, after converted solid condition apply the molded PCM-graphene layer onto the back FPV panel surface, ensuring proper adhesion and coverage. Final two configurations are prepared: a. Solar FPV Panel Without PCM, b. Solar FPV Panel With PCM-Graphene Composite, and also used a digital vernier calliper to measure the thickness of the PCM layer and validate uniformity.

Equipment and DAQ system

The purpose of the system setup was to use a weather station to measure wind speed and a pyranometer to measure sun irradiance. Every variable signal was gathered and documented, including the FPV modules' voltage and surface operating temperatures with an infrared thermometer for the entirety of the tests. Both the reference FPV panel and the FPV-PCM use an MPPT meter to measure voltage, current, and power to determine the V_{OC} , I_{SC} , P_{max} , and efficiency % in the FPV panel circuit. Furthermore, an infrared thermometer is used to examine temperature variations found on the FPV panels' front and rear surfaces at various portions. Temperature measurements have been made at several locations on the panel's surface. Table 3 shows the specifications of the equipment used in the experiments.

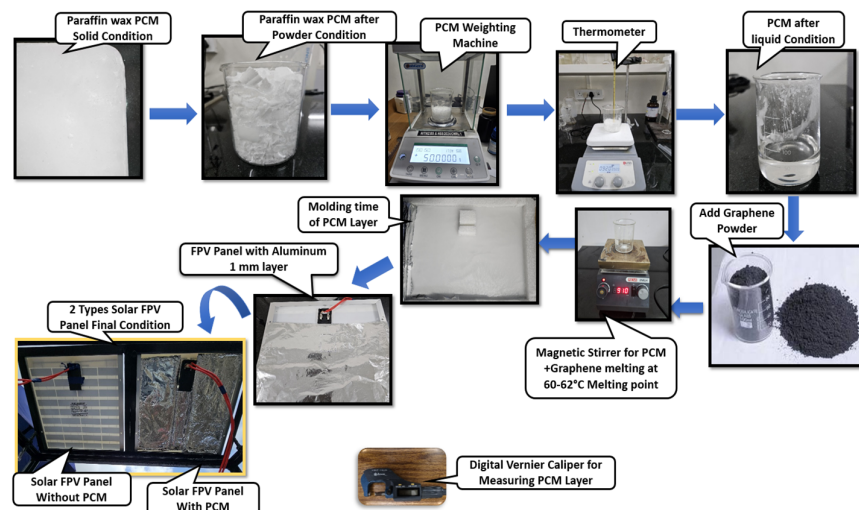


Figure 4. The visual PCM production process

Table 3. Specifications of experimentally used equipment

Sr. No.	Experiment-al equipment name	Sensors	Range	Used for
1.	Metravi Pro Solar MPPT meter	Voltage current Power	12- 60V DC (± 0.1 v) 0 – 35 A (± 0.1) 5-800 W	Maximum Power (P_{max}) Maximum Voltage(V_{mp}) Maximum Current(I_{sc}) Open circuit voltage(V_{oc}) Open circuit current (I_{sc})
2.	Metravi IR Pyranometer MT-8	Temperat-ure Humidity Radian Thermoco- uple	-50 -800°C 20%-80% RH (0.1- 1.00) -10°C-500°C	Environmental temperature Humidity Surface, back side, and water temperature
3.	Metravi Pro IM-09 Solar Energy Tester	compass Solar irradiance Ambient temperatu-re Tilt angle	0- 360° 0-1400 W/m ² ($\pm 5\%$) -30° - 100°C ($\pm 2^\circ$) -90° +90° ($\pm 1.5^\circ$)	Compass Irradiance Ambient and surface temperature Tilt angle
4.	Metravi WS-1051 Wireless Weather Station	Temperat-ure Humidity Wind speed Wind direction Rain Fall	-40°- 60°C 0-99% Speed 0->50 m/s ($\pm 10\%$) 0- 999 mm	Temperatur-e Humidity Wind Speed and Direction Rain fall
5.	Labart 4-Channel K-Type Digital Thermometer Thermocouple Sensor 200~1372°C/2501°F Sensor LT-1372	Temperature	Measurement Temperature range: - 200°C~1372°C (-328°F ~ 2501°F).	Panels front & back surface temperature
6.	Infrared thermal Camera Testo 890	Thermal image	30 to 650°C	Thermal image

Table 4. Specifications of experimentally used equipment

S.No	Measurement Parameters	Measuring Instruments	Uncertainty
1.	Front & back Temperature	4-channel data logger with thermocouples	Thermocouples can have higher uncertainty due to reference junction compensation and non-linearity ($\pm 1-2^\circ$ C).
2.	Water Temperature	Digital thermometer	For water temperature measurement, expect uncertainty between $\pm 0.1^\circ$ C and $\pm 2^\circ$ C, depending on sensor type and calibration.
3.	Ambient temperature	Weather station	weather stations typically have an uncertainty of about $\pm 0.2^\circ$ C to $\pm 0.5^\circ$ C for high-quality
4.	Wind speed	Weather station	High precision, often $\pm 0.1-0.2$ m/s, but sensitive to rain/icing
5.	Humidity	Weather station	typically have an uncertainty of about $\pm 2\%$ to $\pm 5\%$ relative humidity (RH)
6.	Voltage	MPPT meter	Electronics inside the MPPT can drift slightly with ambient temperature, adding $\pm 0.1-0.2$ V error.
7.	Current	MPPT meter	Many MPPT meters display current in 0.1 An increments, so the resolution itself adds ± 0.05 An uncertainty.
8.	Solar Intensity	Pyranometer	A pyranometer typically has an uncertainty of about $\pm 2\%$ to $\pm 5\%$ under standard calibration conditions.
9.	Power Output	MPPT meter	Dust, humidity, temperature drift, and shading can add 1–3% uncertainty.
10.	Tilt angle	Pyranometer	A pyranometer measures irradiance based on its angle relative to the sun. Even small tilt errors ($1-2^\circ$) can cause 1–3% uncertainty in readings.
11.	Emissivity	Infrared thermometer	The uncertainty in emissivity measurement using an infrared (IR) thermometer is typically ± 0.01 to ± 0.05 in the emissivity value.
12.	Panels Length & Width	Scale	NA
13.	PCM weight	Precision balance machine	Air currents, vibration, humidity, and temperature drift can add $\pm 1-5$ mg uncertainty.
14.	PCM Layer	Digital Vernier calliper	Smallest division the calliper can read (0.02 mm for mechanical, 0.01 mm for digital).
15.	PCM melt	Magnetic stirrer	The combined uncertainty in PCM melting temperature measurement using a magnetic stirrer setup is about $\pm 1-3^\circ$ C under laboratory conditions.

Electrical output

An MPPT meter (Metravi Pro Solar, 800 W) was used to measure the electric power of each module during testing, allowing for accurate monitoring of voltage and current. The maximum

power, represented by P_{max} , is determined by taking into account the maximum voltage V_{mp} and the maximum current I_{mp} , as seen below:

The following formula is used to calculate the maximal power (P_{max}):

$$P_{\max} = (I_{\text{mp}} \times V_{\text{mp}}) \quad (1)$$

The maximum voltage and current are indicated by the symbols V_{mp} and I_{mp} , respectively.

The module efficiency is then calculated using the formula below:

$$\eta_e = P/(AG \times 100) \quad (2)$$

The panel area is defined by A (m^2), whereas the incoming solar radiation is defined by G (W/m^2).

Analysis of uncertainty

The following formula, which was first suggested in (Ahn *et al.*, 2019), is used to represent the standard uncertainty for a given instrument, u :

$$u = a/3^{1/2} \quad (3)$$

In this instance, ‘ a ’ denotes precision (Elminshawy *et al.*, 2019). Anxiety about the accuracy of measured values is known as evaluation uncertainty (Lu *et al.*, 2019).

One can use it to calculate the uncertainty of a function M with ‘ n ’ independent linear parameters, such as $M = f(y^1, y^2, \dots, y^n)$ (Lu *et al.*, 2019). Efficiency, power, and temperature were calculated and the independent variable errors of 4.90%, 3.9%, and 3.1%, respectively. Experimentally used equipment and its uncertainty are illustrated in Table 4.

Results and Discussion

The experiment used the weather of Aizawl, Mizoram, India, and was conducted on the National Institute of Technology Mizoram, India campus in April 2025. Thermal and electrical performance was evaluated and compared with a standard reference FPV module (without PCM) for two FPV solar panels with and without PCM at various tilt angles (12° , 18° , 24° , and 30°) for cooling the FPV module. Furthermore, the wind condition was examined with a wind speed (v) of 5 m/s. For

a dependable outcome, the experiment was conducted every day and continually, repeating the factors that were examined. The experimental results and their implied explanation are presented in this section. Comparative trends of the experimentally obtained results for panels inclined at 12° , 18° , 24° , and 30° are presented in Tables 5, 6, 7, 8, 9, 10, 11, and 12, respectively. Each table contains the quantitative values of the panel surface temperature, ambient temperature, irradiance, power, and electrical efficiency for both reference FPV and FPV-PCM Cooling. It is evident from Tables 5 through 12 that all of these factors change significantly as solar irradiation varies. These data make it clear that by utilising PCM’s thermal characteristics, FPV-PCM continuously maintains a lower surface temperature than a standard FPV panel. In summary, by absorbing extra heat during operation, phase change materials (PCM) lower photovoltaic temperatures. The phase change material dissolves and stores thermal energy in the form of latent heat at a nearly constant temperature while the photovoltaic module heats up. Without significantly raising the temperature of the phase transition material, this process limits the growth in photovoltaic temperature. The PCM freezes and releases the stored heat when the outside temperature drops. Additionally, Table 5 through 12 aid in the comparative measurement of the impact of various FPV-PCM Cooling panel inclinations and angles on cooling performance. It has been observed that the FPV-PCM Cooling panel performs better at an angle of 18° than at 12° , 24° , and 30° . Flat panels are particularly vulnerable to reflection losses, which can cause partial or delayed melting. Conversely, a panel with a higher inclination is more likely to get less solar flux, which could lead to partial melting and reduced storage capacity. Additionally, tilt affects PCM’s natural convection. Better convection would result in uniform PCM melting, which would further aid in avoiding PCM stratification. Consequently, the panel’s efficiency increases.

Similar effects of tilt angle have been documented in the literature.

Table 5. FPV panel performance matrix at 12° tilt angle

Time	Ambient Temperature (°C)	Water Temperature (°C)	Irradiance (W/m^2)	Surface Temperature (°C)	Back Surface Temperature (°C)	Current (A)	Voltage (V)	Output Power (W)	Efficiency ($\eta\%$)
9:30 AM	30.5	20.2	250	32	32	0.1	18.7	1.9	7.2
10:30 AM	34.5	20.4	518	35	35	0.1	18.9	2.2	8.9
11:30 AM	35.6	21.3	720	37	37	0.3	18.5	5.6	7.7
12:30 PM	37.2	21.2	695	39	39	0.3	18.5	5.6	7.8
1:30 PM	37.4	24.1	730	45	46	0.3	18.6	7.2	9.8
2:30 PM	35.9	24.0	350	45	46	0.2	17.9	3.1	8.8
3:30 PM	34.4	30.1	765	42	43	0.3	18.9	5.3	6.8

Table 6. FPV-PCM cooling panel performance matrix at 12° tilt angle

Time	Ambient Temperature (°C)	Water Temperature (°C)	Irradiance (W/m ²)	Surface Temperature (°C)	Back Surface Temperature (°C)	Current (A)	Voltage (V)	Output Power (W)	Efficiency (η%)
9:30 AM	30.5	20.2	250	36	24	0.1	18.5	2.2	7.1
10:30 AM	34.5	20.4	518	41	22	0.3	19	5.7	10.9
11:30 AM	35.6	21.3	720	42	23	0.4	18.4	6.3	8.5
12:30 PM	37.2	21.2	695	42	23	0.3	18.3	5.9	7.4
1:30 PM	37.4	24.1	730	41	25	0.4	18.9	7.6	5.9
2:30 PM	35.9	24.0	350	44	27	0.1	17.9	3.9	5
3:30 PM	34.4	30.1	765	49	25	0.4	16.6	6.6	8.4

Table 7. FPV panel performance matrix at 18° tilt angle

Time	Ambient Temperature (°C)	Water Temperature (°C)	Irradiance (W/m ²)	Surface Temperature (°C)	Back Surface Temperature (°C)	Current (A)	Voltage (V)	Output Power (W)	Efficiency (η%)
9:30 AM	30.5	20.2	250	32	30	0.2	18.8	2.5	8.6
10:30 AM	34.5	20.4	518	35	36	0.2	18.8	3	9
11:30 AM	35.6	21.3	720	37	37	0.3	19	5.5	8.4
12:30 PM	37.2	21.2	695	39	37	0.3	18.8	6.7	8.2
1:30 PM	37.4	24.1	730	43	47	0.3	18.7	7.3	9.9
2:30 PM	35.9	24.0	350	43	47	0.2	18.1	3.5	9.6
3:30 PM	34.4	30.1	765	42	42	0.3	18.9	5.4	8.3

Table 8. FPV-PCM cooling panel performance matrix at 18° tilt angle

Time	Ambient Temperature (°C)	Water Temperature (°C)	Irradiance (W/m ²)	Surface Temperature (°C)	Back Surface Temperature (°C)	Current (A)	Voltage (V)	Output Power (W)	Efficiency (η%)
9:30 AM	30.5	20.2	250	37	23	0.2	18.9	2.9	9.8
10:30 AM	34.5	20.4	518	41	23	0.3	19	5.4	13.8
11:30 AM	35.6	21.3	720	43	23	0.4	19.1	6.6	9.2
12:30 PM	37.2	21.2	695	43	24	0.5	18.2	6.8	8.9
1:30 PM	37.4	24.1	730	43	24	0.4	18.9	7.5	10.2
2:30 PM	35.9	24.0	350	45	27	0.3	17.8	3.8	9.5
3:30 PM	34.4	30.1	765	49	24	0.4	17.7	6.7	9.7

Table 9. FPV panel performance matrix at 24° tilt angle

Time	Ambient Temperature (°C)	Water Temperature (°C)	Irradiance (W/m ²)	Surface Temperature (°C)	Back Surface Temperature (°C)	Current (A)	Voltage (V)	Output Power (W)	Efficiency (η%)
9:30 AM	30.5	20.2	250	31	30	0.2	17.9	2.3	8.3
10:30 AM	34.5	20.4	518	36	37	0.1	18.2	2.9	8.8
11:30 AM	35.6	21.3	720	39	39	0.3	18.5	5.1	8.2
12:30 PM	37.2	21.2	695	40	39	0.3	18.8	6.1	8
1:30 PM	37.4	24.1	730	43	48	0.4	18.5	7	9.4
2:30 PM	35.9	24.0	350	44	46	0.1	18	3.3	9.1
3:30 PM	34.4	30.1	765	43	44	0.2	18.1	5.1	8.1

Table 10. FPV-PCM cooling panel performance matrix at 24° tilt angle

Time	Ambient Temperature (°C)	Water Temperature (°C)	Irradiance (W/m ²)	Surface Temperature (°C)	Back Surface Temperature (°C)	Current (A)	Voltage (V)	Output Power (W)	Efficiency (η%)
9:30 AM	30.5	20.2	250	38	23	0.2	18.1	2.8	9.8
10:30 AM	34.5	20.4	518	42	22	0.3	18.5	5	12.3
11:30 AM	35.6	21.3	720	43	23	0.3	18.8	6	9
12:30 PM	37.2	21.2	695	43	24	0.4	18.2	6.3	8.2
1:30 PM	37.4	24.1	730	44	24	0.3	18.5	7.3	9.8
2:30 PM	35.9	24.0	350	45	28	0.3	18.3	3.5	9.3
3:30 PM	34.4	30.1	765	50	24	0.3	18.5	6.3	9.4

Table 11. FPV panel performance matrix at 30° tilt angle

Time	Ambient Temperature (°C)	Water Temperature (°C)	Irradiance (W/m ²)	Surface Temperature (°C)	Back Surface Temperature (°C)	Current (A)	Voltage (V)	Output Power (W)	Efficiency (η %)
9:30 AM	30.5	20.2	250	31	31	0.2	17.2	2.2	7.9
10:30 AM	34.5	20.4	518	36	37	0.1	17.9	3	8.1
11:30 AM	35.6	21.3	720	38	39	0.3	18	4.9	9.1
12:30 PM	37.2	21.2	695	39	36	0.2	18.3	6	7.8
1:30 PM	37.4	24.1	730	43	48	0.3	18.6	6.8	9.1
2:30 PM	35.9	24.0	350	43	46	0.1	18.1	3.1	9
3:30 PM	34.4	30.1	765	42	44	0.2	17.5	5	8

Table 12. FPV-PCM cooling panel performance matrix at 30° tilt angle

Time	Ambient Temperature (°C)	Water Temperature (°C)	Irradiance (W/m ²)	Surface Temperature (°C)	Back Surface Temperature (°C)	Current (A)	Voltage (V)	Output Power (W)	Efficiency (η %)
9:30 AM	30.5	20.2	250	38	24	0.1	17.9	2.7	9.1
10:30 AM	34.5	20.4	518	42	24	0.3	18.3	4.5	11.9
11:30 AM	35.6	21.3	720	43	24	0.2	18.2	5.7	10.1
12:30 PM	37.2	21.2	695	43	25	0.4	18.5	6.1	8.1
1:30 PM	37.4	24.1	730	43	25	0.2	18.6	7	9.8
2:30 PM	35.9	24.0	350	44	28	0.3	18.3	3.3	9.1
3:30 PM	34.4	30.1	765	49	25	0.1	17.6	5.9	9

The average efficiency improvement across the systems or experimental groups under study is shown in Table 13. A clear indication of relative performance gains is provided by the percentages used to convey the data. The table displays the 95% confidence interval (CI), which shows the statistical precision of the estimate, next to each mean value.

Table 13. Mean efficiency improvement (%) with 95% confidence intervals

Condition	Mean Efficiency Improvement (%)	95% CI
FPV panel with PCM Cooling	12.22	9.60, 14.84
FPV panel without PCM Cooling	9.53	7.11, 11.53

Electrical Analysis

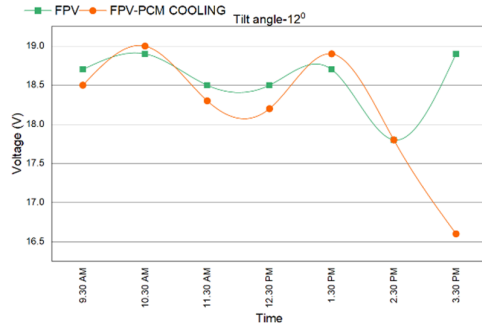
The electrical qualities can be evaluated by looking at how the power, voltage, and current parameters changed during the experiment. Figure 5 shows how the FPV-PCM cooling's voltage profile relates to the FPV at various tilt angles of 12°, 18°, 24°, and 30°. The I-V (current-voltage) and P-V (power-voltage) curves, which serve as the two essential graphs for characterising FPV modules, are illustrated in Figure 6 and 7, featuring both the PCM Cooling panel and the plain panel at different tilt angles (12°, 18°, 24°, and 30°).

Maximum current values occur between 9:30 AM and 2:00 PM due to the moderate temperature of the panel and increased sun irradiation. Overall, the maximum current

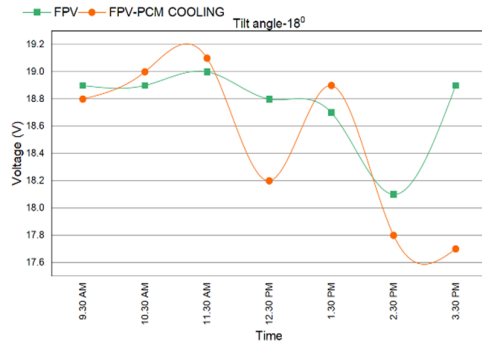
generated by the recommended configuration is 14.02% more than that of the reference panel. Additionally, when looking at the average current, the FPV-PCM generates a higher current output than the FPV panel. The power output is calculated by multiplying the output voltage by the current. The output power comparison of the FPV panel and the FPV-PCM cooling is displayed in Figure 9.

Experimental results show that the maximum electrical power output of a reference FPV panel is 7.2 W when the solar radiation is 790 W/m². On the other hand, when 12 mm of paraffin wax and graphene mixed PCM with a 1 mm aluminium layer is employed, and the tilt angles are 12°, 18°, 24°, and 30°, the highest electrical power production of the FPV-PCM panel is 7.6 W at the same level of solar radiation. Since the amount of power generated drastically decreases after 3:30 PM, this power range is related to the hours of 9:30 AM to 2:30 PM. On the other hand, the initial phase of exploration is the focus of the maximum power obtained from both configurations.

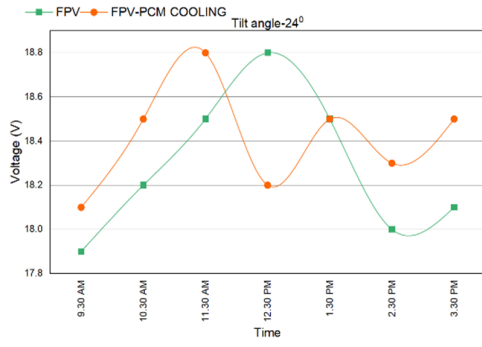
Efficiency produced by FPV and FPV-PCM cooling over the experimental period at the optimal tilt angles (a) 12°, (b) 18°, (c) 24°, and (d) 30° is shown in Figure 10. The combination of the FPV-PCM cooling improves efficiency by an average of 13.55% as compared to the FPV alone, and the 18° tilt angle has better efficiency compared to other tilt angles. The FPV-PCM Cooling system operates at a lower temperature at an 18° inclination, which greatly reduces entropy formation associated with irreversible heat rejection.



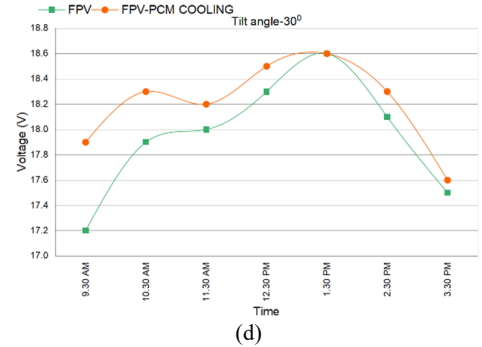
(a)



(b)

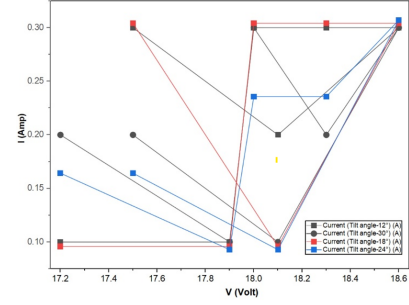


(c)

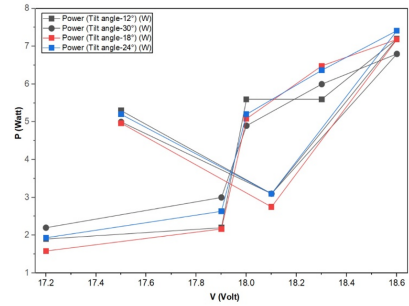


(d)

Figure 5. The FPV-PCM Cooling's voltage profile relates to the FPV at various tilt angles of (a) 12°, (b) 18°, (c) 24°, and (d) 30°

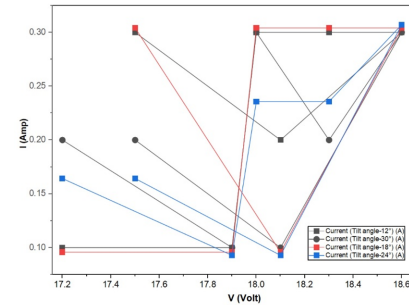


(a) I-V Curve of FPV Plain panel

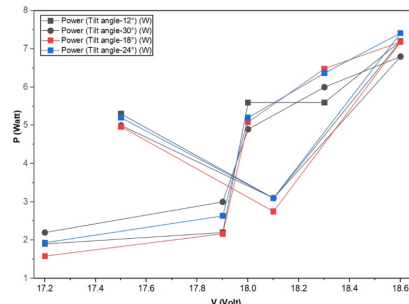


(b) P-V Curve of FPV Plain panel

Figure 6. The FPV Plain panel I-V and P-V Graph at various tilt angles of 12°, 18°, 24°, and 30°

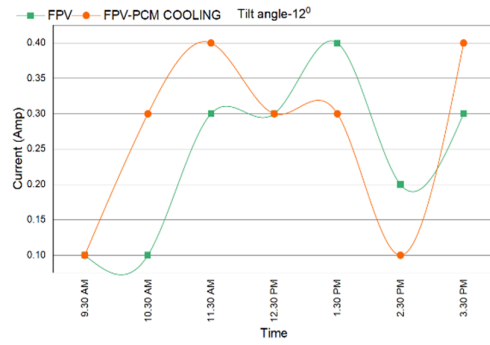


(a) I-V Curve of FPV Plain panel

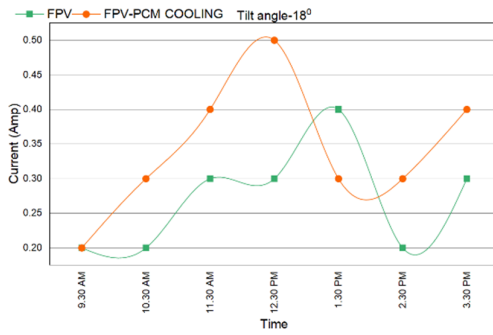


(b) P-V Curve of FPV Plain panel

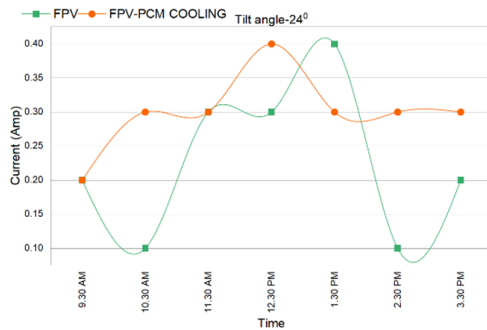
Figure 7. The FPV-PCM Cooling panel I-V and P-V Graph at various tilt angles of 12°, 18°, 24°, and 30°



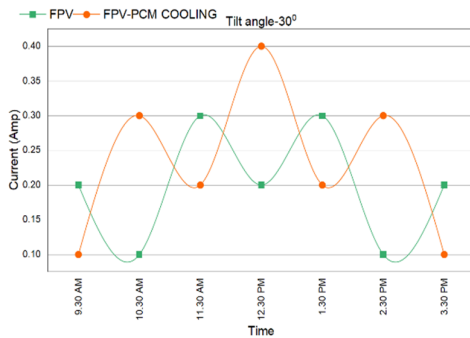
(a)



(b)

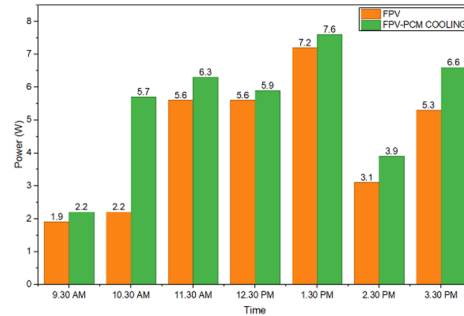


(c)

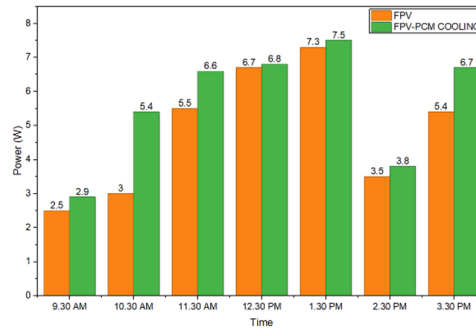


(d)

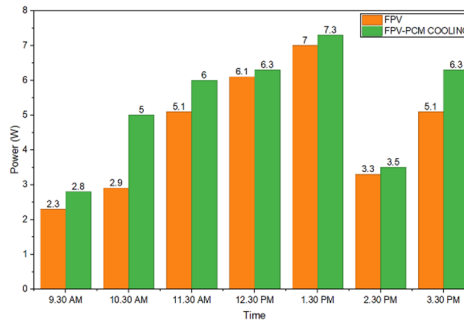
Figure 8. The FPV-PCM Cooling's current profile relates to the FPV at various tilt angles of (a) 12°, (b) 18°, (c) 24°, and (d) 30°



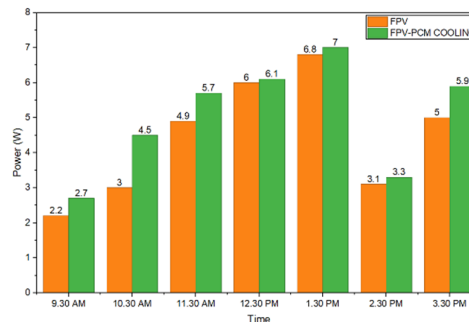
(a)



(b)



(c)



(d)

Figure 9. The FPV-PCM Cooling's output power profile relates to the FPV at various tilt angles of (a) 12°, (b) 18°, (c) 24°, and (d) 30°

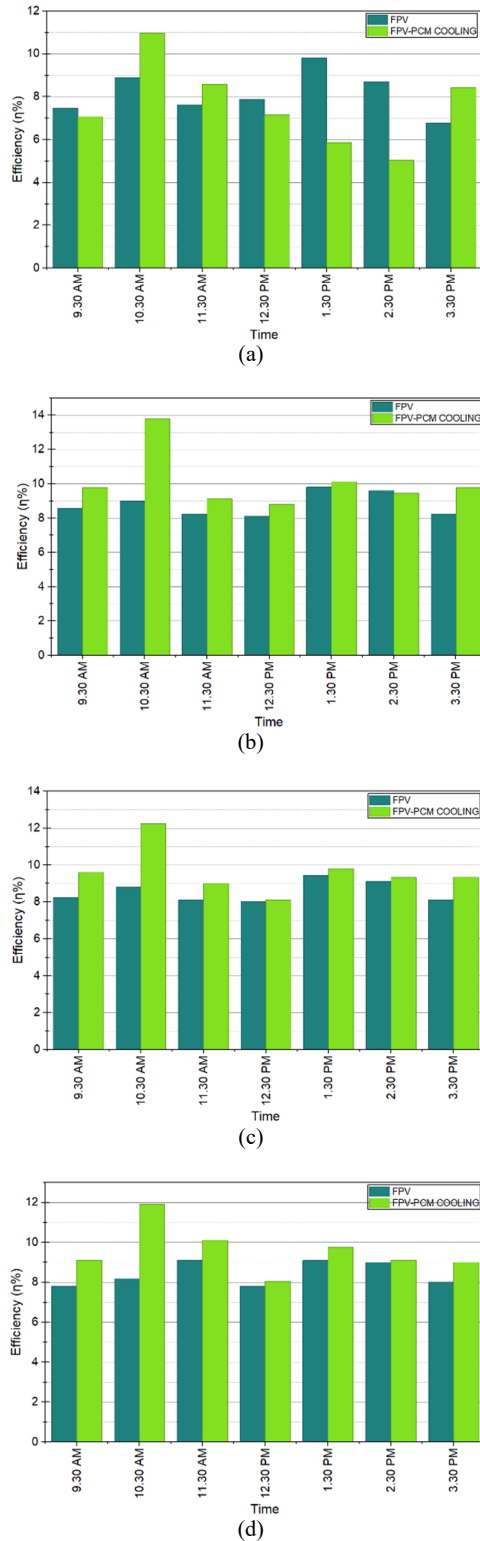


Figure 10. The FPV-PCM Cooling's efficiency profile relates to the FPV at various tilt angles of (a) 12°, (b) 18°, (c) 24°, and (d) 30°

Thermal Analysis

It is anticipated that the new FPV-PCM cooling system will enhance the convection area exposed to different media (water on the lower side and air on the upper side), which will speed up the removal of surplus heat from the panel surface. As a result, the FPV module operating temperature based on the PCM cooling setup was included in the experiment results in this section.

First, the thermal performance of the FPV modules under examination was assessed outdoors with no water current present and an ambient wind speed of less than 0.1 m/s, which is equivalent to still air.

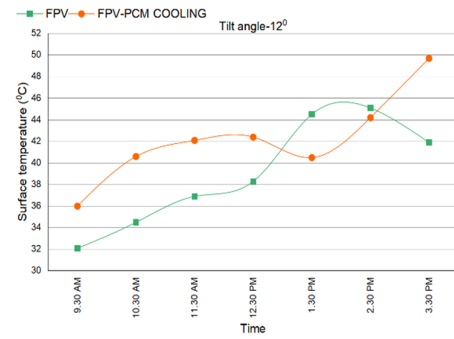
By comparing the temperature readings for the two designs at various times and with varying irradiation intensities, the thermal characteristics are investigated. An infrared thermometer is used to measure the solar FPV temperature, and Table 14 provides the calibration parameters that correlate to that measurement.

Table 14. Infrared thermometer calibration details

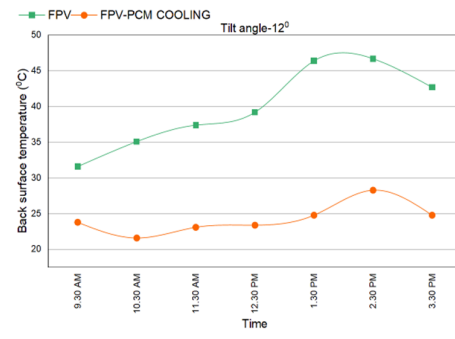
Specifics	Value
Emissivity ϵ	0.95
Distance of an Object	1.2 m
The relative humidity level	53%
The temperature of the reference atmosphere	22°C

The backside of the FPV panel typically shows a higher temperature because of decreased convection and heat loss from radiation on this side. It is also clear that the upper surface temperature of the FPV-PCM cooling panel is significantly lower than that of the FPV panel. This problem is related to the panel's orientation and results from insufficient air circulation beneath the panel, which lowers the rate of heat loss through forced convection in comparison to the upper surface of the FPV panel. On the other hand, FPV-PCM increases the efficiency of heat transfer rates by creating a poor heat resistance channel on the back surface of the PCM panel. Figure 11 shows the foundation of the time-surface temperature graph at the various tilt angles: (a) 12°, (b) 18°, (c) 24°, and (d) 30°.

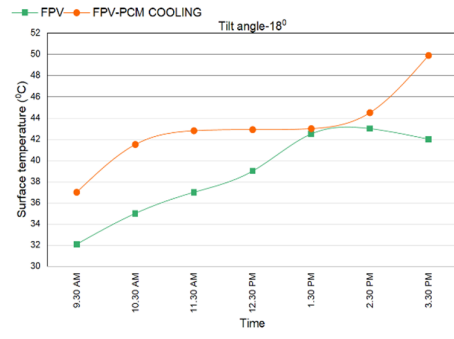
Temperature measurements involving the FPV panel's upper surface are required in order to analyse the thermal properties of the FPV-PCM cooling arrangement. Examining the temperature differences between these three surfaces, it can be shown that when the FPV is submerged in water and PCM, its topmost surface remains warmer than the others. Basis of time: Figure 12 shows the back surface temperature graph at the various tilt angles: (a) 12°, (b) 18°, (c) 24°, and (d) 30°.



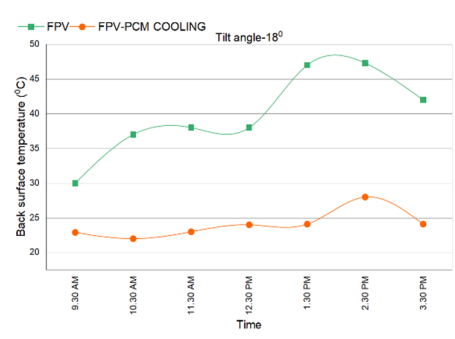
(a)



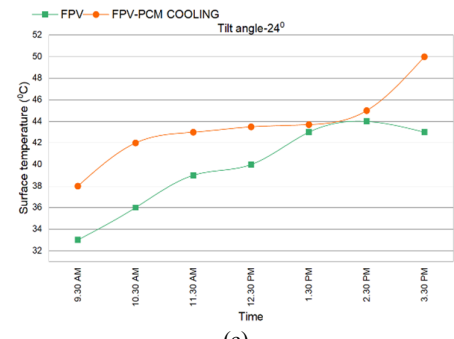
(a)



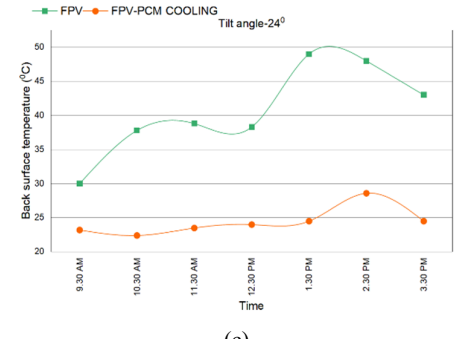
(b)



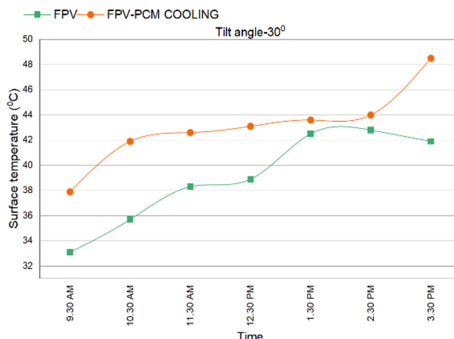
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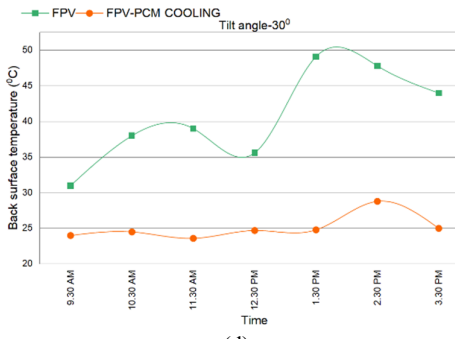
(c)



(c)



(d)



(d)

Figure 11. The FPV-PCM Cooling's surface temperature profile relates to the FPV at various tilt angles of (a) 12°, (b) 18°, (c) 24°, and (d) 30°

Figure 12. The FPV-PCM Cooling's back-surface temperature profile relates to the FPV at various tilt angles of (a) 12°, (b) 18°, (c) 24°, and (d) 30°

The thermal image in Figure 13 delineates the differences between two FPV panels—one that utilises PCM cooling (Panel A) and another that is plain (Panel B), focusing on the disparities in surface temperature. Panel 'A' presents cooler sections (blue-green), highlighting the successful heat mitigation achieved with phase change materials at 3:30 pm (irradiance 790 W/m², mentioned in Figure 14), the peak time of solar irradiance. Panel B is characterised by a uniformly warmer tone (green-yellow), which suggests a greater level of thermal stress without the benefit of cooling enhancement.

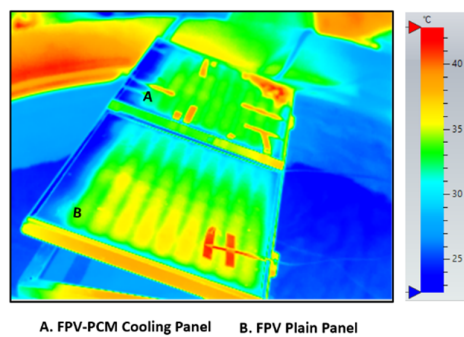


Figure 13. Thermal images of FPV-PCM Cooling panel and FPV Plain panel during investigation of the solar irradiance peak time

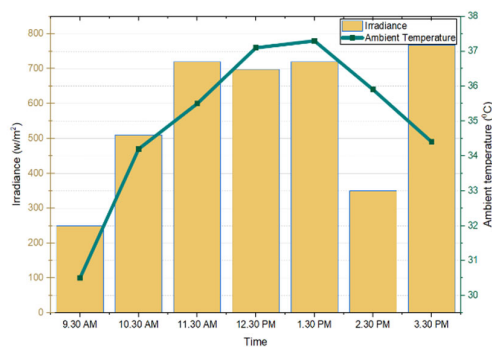


Figure 14. The hourly measurements of ambient temperature and solar radiation

Climate and water properties

In April, Mizoram's daily weather conditions were essentially the same, with a small fluctuation that had a negligible impact on the FPV module's thermal and electrical performance when used outdoors. At the testing location, which is located in Aizawl, Mizoram, India, the air temperature and the amount of solar radiation were all tracked during the

trial. Figure 14 displays the hourly measurements of ambient temperature and solar radiation.

The hours of 11:30 am to 1:30 pm and repeat at 3:30 pm had the highest levels of solar radiation. Up until midday, solar radiation rose steadily; after that, it began to fall as evening approached. Throughout the test days, the maximum solar radiation intensity ranged from 760 W/m² to 790 W/m²; a small fluctuation in the mean solar radiation was noted during the test days. The same figure also included a plot of the variation in the ambient temperature. Up until noon, the outside temperature was trending upward; at the end of the day, however, it started to fall. Figure 15 illustrates the relationship between time and water temperature in the graph.

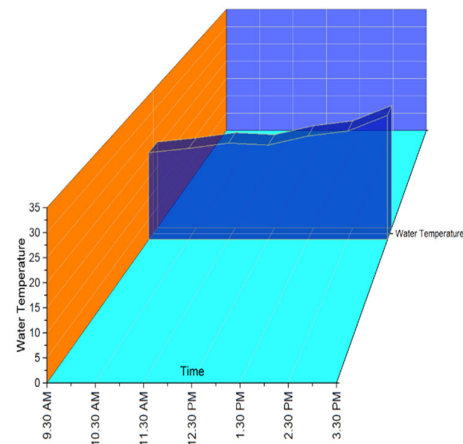


Figure 15. Graphical view of the hourly measurements of water temperature

Compared to FPV and other tilt angles, the FPV-PCM 18° tilt angle has a lower back surface temperature, greater thermal performance, and fewer heat losses, according to observations of the top and back surface temperatures.

Figure 16 shows that the average surface temperature drop observed in FPV systems with PCM cooling panels is compared to that without. The integration of PCM Cooling panels enhances cooling efficiency, resulting in a greater reduction in surface temperature.

Effect of Wind Speed on Cooling Efficiency and Power Enhancement

The speed of the wind significantly contributes to the cooling efficiency of Floating Solar PV systems that incorporate Phase Change Materials (PCM), leading to a greater power output. Enhanced airflow reduces the temperature of the

panel surfaces, which lessens thermal losses and increases electrical efficiency. Figure 17 shown that 9:30 am to 3:30 pm wind speed data during the experiment time. On the other hand, excessive wind can create mechanical stress and cause uneven cooling.

- Wind facilitates increased convective heat transfer from photovoltaic surfaces, thereby lowering the operating temperature.
- During peak solar hours, Phase Change Materials (PCM) take in heat; the presence of wind facilitates their cooling recovery by hastening heat dissipation.
- Reduced temperatures contribute to lower resistive losses in photovoltaic cells, thereby increasing conversion efficiency by 2-5%.

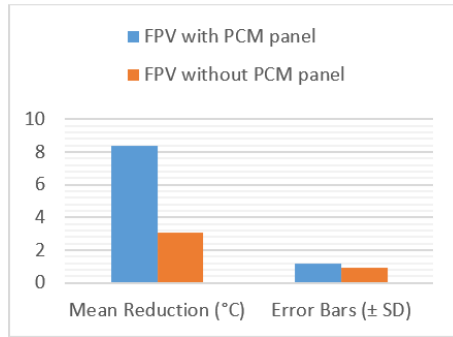


Figure 16. Average surface temperature drop (°C) between FPV with and without PCM Cooling panels

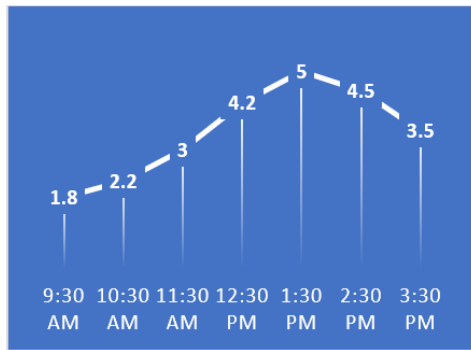


Figure 17. The hourly measurements of ambient temperature and solar radiation

In Mizoram, the average wind speeds are generally moderate, falling between 2 and 5 m/s, with seasonal differences. The winds are particularly stronger in the pre-monsoon season, which occurs from March to May. In the experiment

time wind speed was measured by the Metravi WS-1051 Wireless Weather Station (already mentioned in table 3). When the wind speed is 5 m/s, and the direction is 57°, at a tilt angle of 18°, then the efficiency of the FPV-PCM Cooling panel exceeds that of the FPV plain panel by 13.55%.

Analyses of the Economy and Environment

Equations 3 through 5 (Almeshaal *et al.*, 2024; Banerjee and Roy, 2026) are used to calculate the 10W FPV panel's energy-saving capacity (E_s).

$$E_{s/d} = E_{pv-PCM} - E_{pvr} \quad (3)$$

$$E_{s/d, 1 \text{ kw}} = E_{s/d} * 4 \quad (4)$$

$$E_{s/r, 1 \text{ kw}} = E_{s/d, 1 \text{ kw}} * \text{No. of Days} * \text{No. of Years} \quad (5)$$

Equation 6 is used to calculate the CO₂ reduction by FPV and FPV-PCM cooling systems in a similar manner (Banerjee and Roy, 2026; Saha *et al.*, 2026).

$$\phi_{CO_2} = \frac{\psi_{CO_2} * E_{Overall}}{1000} \quad (6)$$

The FPV-PCM Cooling system produces an additional 23.42 Wh per day for a 1 kW installation, which is equivalent to about 9.15 kWh annually and more than 220 kWh over a 25-year operating lifespan, according to the measured average power enhancement at an 18° tilt. The extra energy generated by the FPV-PCM Cooling system at an 18° tilt reduces CO₂ by around 7.1 kg per year for a 1 kW installation, a total 168 kg of mitigated emissions throughout a 25-year lifespan, using an Indian grid emission factor of 0.79 kg CO₂ kWh⁻¹.

Comparing the Current Investigation to Previous Research Articles

Table 15 compares the FPV-PCM Cooling system performance parameters from the current analysis with those reported in previous studies. The effectiveness of the created FPV-PCM Cooling setup is supported by the higher performance of the recommended FPV-PCM Cooling systems when compared to earlier research. Furthermore, it is important to highlight that the PCM thickness used in the current setup is only 12 mm, but the PCM thicknesses listed in the literature are 18 and 30 mm. Table 15 shows that a higher effectiveness is attained in comparison to the literature, even with less material thickness, indicating that the present setup is more affordable than the literature. The best thermal alignment between PV heat generation and the latent heat capacity of the PCM is responsible for the increased efficiency seen in this study using

a thinner PCM layer (12 mm) compared to prior studies using a 18 mm and 30 mm PCM. For realistic photovoltaic systems, the decreased PCM thickness results in material savings of about 48%, improving cost effectiveness and scalability. While thinner PCM layers result in improved thermal reactivity and efficiency for flat-plate FPV operating under natural convection, thicker PCM layers may improve performance in high-flux or concentrated FPV cooling systems.

Table 15. FPV-PCM Cooling Performance Comparison with Past Research

Reference	Efficiency Increase	Used Technology in FPV
Present Work	13.55%	PCM Composite (96% paraffin wax and 4% graphene) with 1 mm aluminium layer
(Arunkumar <i>et al.</i> , 2024)	12.08%	Jute Cloth layer and jet impingement
(Elminshawy <i>et al.</i> , 2023)	12.26%	Fin arrays
(Sutanto <i>et al.</i> , 2022)	4.52%	Thermosiphon
(Ho <i>et al.</i> , 2015)	2.03 %	Microencapsulated PCM 30 mm layer

In summary, conduction from the FPV back-surface to the PCM enclosure, natural convection within the liquid PCM Cooling during the phase transition, and latent heat absorption during melting are the three main heat transfer mechanisms that control the thermal management of the FPV-PCM Cooling system.

PCM Cooling's Difficulties, Constraints

While PCMs provide substantial potential for cooling PV systems, there are important challenges and limitations that influence their effectiveness and scalability. These obstacles include material constraints, integration problems, and long-term reliability issues, all of which must be resolved for broad adoption. When used in PV cooling systems, PCMs' performance, durability, and general sustainability may be impacted by their intrinsic material limits, despite the fact that they offer efficient passive temperature regulation. For effective and long-lasting integration into FPV modules, the two main kinds of PCMs (Togun *et al.*, 2025), organic and inorganic, present unique advantages and difficulties that call for careful consideration.

To enhance their cooling effectiveness, the integration of PCM into FPV systems brings forth several technological and design issues that must be carefully resolved. The main challenges include the

effective incorporation of PCM materials into FPV modules, dealing with structural and installation problems, ensuring compatibility with existing FPV components, and understanding the complexities of hybrid systems that combine PCM with various cooling techniques.

Long-Term Reliability & Maintenance Cost

The long-term dependability of PCM cooling systems presents another significant challenge, given that PCMs are prone to deterioration after undergoing multiple thermal cycles. The process of phase change, which includes ongoing melting and solidification, may result in material fatigue and alterations in the structure of the PCM, thereby impacting its thermal efficiency as time progresses. Even though PCM cooling offers remarkable benefits for enhancing FPV efficiency, these systems are confronted with challenges related to materials, integration, and durability that need to be effectively managed to secure long-term viability and sustainability. Finally, enhancing the scalability of PCM-based cooling systems for extensive FPV installations and minimising the expenses related to PCM materials and their integration represent significant research challenges. Regular maintenance is fairly low, mainly requiring the inspection of PCM integrity and the cleaning of FPV modules. Long-term costs stay reasonable as PCM materials are durable and FPV structures demand minimal maintenance.

Research focused on reducing these costs via mass production methods and innovations in materials will be crucial in establishing PCM cooling systems as a widely adopted solution for photovoltaic (PV) installations globally.

Conclusions

A comprehensive experimental study of a unique cooling technology as a recently created PCM for controlling the operating temperatures of a freestanding floating solar module (FPV) is presented in this research. A single PCM was investigated for cooling the FPV module, and its electrical and thermal performance was contrasted with that of a standard FPV module (without PCM Cooling). The present study came to the following conclusion:

- The results demonstrate that the application of PCM to the back surface of the FPV panel significantly lowers surface temperature by 4.10% at 12°, 8.77% at 18°, 7.10% at 24° and 6.94% at 30°.
- The FPV-PCM Cooling system produces 23.42 Wh per day for a 1 kW installation,

which is equivalent to about 9.15 kWh annually and more than 220 kWh over a 25-year operating lifespan.

- In comparison to the baseline FPV system, the PCM-FPV system reduced the backside temperature by 8.77 °C, resulting in an 18% increase in thermal regulation.
- When the wind speed is 5 m/s, and the direction is 57°, at a tilt angle of 18°, the efficiency of the FPV-PCM Cooling panel is 13.55% higher than that of the FPV plain panel, when paraffin wax and graphene mixed PCM with a thickness of 12 mm is utilised.

Future Scope

The quantifiable rates of water conservation and the total decrease in evaporation will be the focus of future research. More research should be done on this and other comparable cooling techniques in the future. By taking into account different perforation sizes and arrays, wind angle of attack, and wind speed, the authors hoped to maximise the cooling efficacy of the perforated fins in subsequent research. The velocity component flow through the hole, the development of perforated tips, and the stability of the conduction through the PCM material are some of the variables that would be critically analysed by computational analysis. In order to improve cooling efficiency, future research may focus on enhancing heat transmission within the PCM layer by adding fins or porous conductive structures. It may also look into hybrid PCM systems with staggered melting temperatures. To evaluate performance under varied environmental conditions and frequent heat cycling, extensive seasonal testing is required. The creation of new and more efficient PCM materials is vital for the sustained success of PCM-based cooling in photovoltaic systems. As current PCMs, both organic and inorganic, exhibit limitations concerning their thermal performance, material costs, and environmental impact, researchers are examining a range of innovative materials to tackle these problems.

Nomenclature

A	Panel surface area [m ²]
C	Specific heat capacity [kJ/kg. k]
CO	Solid heat capacity [kJ/kg. k]
G	Solar radiation intensity [W/m ²]
I	Current [A]
k	Thermal conductivity [W/m. K]
P	Power [W]

PS	Saving power [W]
t	Time [hr.]
T	Temperature [°C]
Ts	Solid temperature [°C]
V	Voltage [V]

Greek symbols

ρ	Density [kg/m ³]
η	Efficiency of solar panels [%]
β	Volumetric expansion coefficient
θ	Tilt angle [°]

Abbreviation

FPV	Floating Solar Photovoltaic system
NCT	Novel cooling technology
PCM	Phase change material
LPV	Land-based Solar Photovoltaic
E _{s/d}	Energy savings per day
Ø _{CO2}	CO ₂ reduction
ψ _{CO2}	CO ₂ emission factor

Subscripts

amb	ambient enhancement
ele	electrical
inc	incident liquid max maximum
oc	Open circuit
sc	Short circuit

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Author Contributions

Conceptualization: M.B.; Methodology: M.B.; Investigation: M.B., S.R.; Data Curation: M.B.; Writing - Original Draft: M.B.; Writing - Review & Editing: M.B., S.R.; Supervision: S.R. All authors have read and agreed to the published version of the manuscript.

Ethics Statement

Ethical approval was not required for this study because it did not involve human participants, animals, identifiable personal data, or materials requiring institutional ethical review.

Declaration of Generative AI Use

The authors declare that no Generative AI tools were used in the preparation of this manuscript.

Conflict of Interest

The authors declare that they have no conflicts of interest related to this work.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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