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Enhancing Photovoltaic Performance Using Phase Change Material (PCM): An Experimental Approach

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Abstract: Photovoltaic (PV) systems have emerged as a leading solution for sustainable energy generation. However, the performance of PV modules deteriorates with increased operating temperatures. This study investigates the enhancement of PV performance through the integration of a phase change material (PCM), specifically paraffin wax, to enable passive thermal regulation. An experimental setup was developed using two identical 20 W PV panels, one integrated with PCM and the other as a control. Over a period of three months in Guwahati, India, real-time measurements were recorded to evaluate thermal and electrical performance. Results revealed that the PCM-integrated panel consistently outperformed the conventional panel, with output power improvements of up to 13.1% and a corresponding surface temperature reduction of over 30%. This research underscores the effectiveness of PCM in improving the thermal stability and energy yield of PV systems.

Keywords: *Photovoltaic; Phase Change Material; Paraffin Wax; Passive Cooling; Performance Enhancement, Surface Temperature.*

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I. INTRODUCTION

Solar energy represents a clean, renewable, and abundant resource with significant global potential. Photovoltaic (PV) technology, which converts solar radiation directly into electrical energy, has witnessed rapid growth due to falling costs and environmental incentives. Despite its benefits, PV system efficiency is adversely affected by elevated module temperatures, a phenomenon particularly pronounced in regions with high solar insolation. Increased panel temperatures cause a reduction in voltage output and overall system efficiency. Thermal management of PV modules has thus become a key research focus. Several passive and active cooling methods have been explored, including heat sinks, water cooling, air ventilation, and phase change materials (PCMs). PCMs are materials capable of storing and releasing substantial latent heat during phase transitions, typically between solid and liquid states. Paraffin wax is one of the most commonly used PCMs due to its favorable thermal properties, affordability, chemical stability, and high latent heat of fusion. In order to solve water scarcity and environmental problems, it is possible to produce enhanced per capita energy in a sustainable manner by investigating solar energy, PV cell efficiency, cooling techniques, and solar stills using phase change materials [5]. The exhaustion of fossil fuels is driving a growing demand for renewable energy; in India, solar energy's potential is highlighted, and as temperature affects panel performance, cooling techniques are being investigated for improved PV production and energy efficiency [6]. The investigation emphasizes the vitality of solar energy in light of fossil fuel and climate change issues. It introduces innovative methods like front cooling with water and active cell surface cooling to improve the efficiency of solar PV panels and work toward the development of effective and environmentally friendly solar energy systems [7] They discovered that immersing solar PV panels in water to a depth of 20 mm raised efficiency to 15.54%, providing better cooling along with potential improvements in energy output [8].The study looks into how different cooling techniques, such as water immersion and active procedures, might improve the efficiency of photovoltaic panels. It shows that water immersion, reflectors, and heat sinks can result in large efficiency gains [9].Active cooling techniques for photovoltaic (PV) panels, including water spraying, can yield significant improvements in efficiency under a number of situations by lowering temperatures, improving power output, and reducing reflection losses [10] .By reducing heat-related losses, cooling techniques such as the application of PCMs are essential to improve the output and efficiency of solar panels [11]. Malaysia's environment is ideal for solar energy use, as shown by the country's annual average solar radiation of 4.21–5.56 kWh/m². On the other hand,

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excessive radiation levels may cause PV panels to overheat, which could reduce their efficiency [12]. PCM cooling devices have been shown in outdoor studies to have the potential to increase solar panel efficiency; nevertheless, as panel temperature increased owing to increased irradiation levels, efficiency decreased [13]. Nigeria prioritizes solar energy generation because of its constant sunshine, and cooling techniques like heat sinks and water spraying have showed promise in preserving PV module efficiency even in the face of temperature rises brought on by exposure to sunlight [14]. In order to improve PV system performance, including less cell deterioration, increased thermal and electrical efficiency, and longer module lifespans, the research thoroughly investigates a variety of cooling strategies [15]. It delves deeply into the incorporation of phase change materials (PCMs) into domestic heating systems, examining how they might reduce emissions, lessen dependency on fossil fuels, and contribute to a future that is more environmentally friendly. For engineers and researchers working on PCM applications, it is an invaluable resource [16]. It also looks into CPC-PV systems and PV panels, showing how cooling significantly improves power output. Because an established model can anticipate this performance with accuracy, CPC-PV is a sensible and affordable option for increased electricity efficiency in hot regions [17]. Thermal performance in PCM-integrated PV systems largely depends on PCM thermal mass, conductivity, and container conductivity, according to an evaluation of five PCMs with different properties; CaCl2 and C-P stand out as the best options for temperature reduction under varying insolation, demonstrating their economic viability in hot climates [18]. It addresses how operating temperature affects commercial silicon-based solar cells and modules and offers tabulated algebraic forms that demonstrate how temperature affects solar power and efficiency, along with correlations for various PV configurations [19]. The study shows that irradiance, temperature, humidity, and dust deposition are among the elements that affect PV module performance. Water cooling reduces the impacts of temperature and increases efficiency, producing the best output power under particular circumstances [20]. The idea uses water as a heat-absorbing medium to dramatically reduce cell temperatures, increasing electrical energy generation by 12%. However, the module's hefty 200 kg weight makes it difficult to place on a typical roof [21]. An 8% increase in electrical efficiency is shown at a module temperature of 65°C when the effects of water cooling on solar modules are studied [22]. Vital cooling preserves an optimal working temperature of 38°C and increases electrical efficiency by approximately 12.5% in an integrated PV/T system, reducing the detrimental effects of high operating temperatures on PV cell performance in an efficient manner. [23]. PV panels with and without fins are compared, and the results show that higher solar radiation increases power and efficiency at the expense of higher heating. Fins are a useful tool for lowering panel temperature and improving energy, output power, and exergy efficiency [24].In order to improve daily freshwater yields, energy, and energy efficiency, the project investigates solar stills connected with PCM storage and enhancements (PF and SWF). The best productivity is achieved by combining PCM and PF, and matching cost studies reflect the improved energy efficiency provided by PCM and SWF [25]. Due to its enhanced transient energy balance and cooling effect, combined PCM shows more significant promise than pure PCM integration. However, the effectiveness of PCM cooling is dependent on comparative convective coefficients. The experimental study shows that both pure and combined PCM integration reduce PV panel temperature, boosting electrical efficiency by 3.0% and 5.8%, respectively [26]. Using a mathematical model to study temperature control and efficiency improvements, the integration of Phase Change Material stuffed rotatable shutters increases PV panel efficiency by up to 9% in hot, humid circumstances [27]. New hybrid photovoltaic-thermal technologies with embedded Phase Change Materials (PCM) appear to have improved electrical efficiency due to improved heat transmission and storage, according to numerical and experimental investigations [28].

PCM and graphene/water nanofluid integration greatly increases thermal and electrical efficiency in a unique hybrid PV/T system, reducing PV panel temperature and improving system performance overall [29]. The promise of PCM-based cooling for increased energy efficiency is validated by a 5.9% yearly electrical energy yield improvement observed when paraffin-based PCM is embedded with PV panels in the hot climate of the UAE [30]. The study investigates the use of palm wax PCM in several containers for PV module passive cooling. It finds that the finned container is the most efficient, resulting in a 4.8% gain in performance ratio and a drop in temperature of 6.1°C and 5.3% increase in efficiency [31]. In ground-source heat pump residential heating, a comprehensive numerical model evaluates thermal storage potential using hybrid water/PCM systems for load shifting. It shows a reduction of 65% in storage volume while achieving an effective off-peak load shift within limited temperature ranges and packing ratios [32]. It focuses on waste heat recovery employing hybrid water and organic PCM systems for thermal energy storage (TES) in Canada's residential sector. In order to maximize energy storage and efficiency, it entails parametric research, system analysis, validation, and numerical modeling [33].

Through experimental and computational studies, it looks at the application of PCMs in building-integrated photovoltaic (BIPV) systems for temperature management, highlighting the effect of fins, PCM characteristics, and system design on improving energy conversion efficiency [34]. Experimental verification of an inventive cooling method for solar PV panels employing Phase Changing Material (PCM) and an aluminum sheet as a Thermal Conductivity Enhancer (TCE) shows a 24.4% average efficiency improvement and a 10.35 °C temperature drop, indicating improved PV performance [35].

In comparison to panels without phase change material (PCM), it achieves a 13.29% temperature reduction and 5.68% efficiency boost using a passive cooling technique for photovoltaic (PV) panels that uses a matrix of copper foam embedded with multi-walled carbon nanotubes [36]. This shows the potential of PCM for effective temperature regulation and improved PV performance.PCM and Al_2O3 nanoparticles are used in PV-building integrated systems.

The study's findings show that adding nanoparticles improves temperature regulation and efficiency by 13.2% and 5.7% when PV and PCM are combined [37]. In order to increase cooling and efficiency, it introduces a unique PV/T system that integrates nanofluid and nano-PCM. Its prediction and optimization of performance is based on Artificial Neural Networks (ANN), validated experimentally in Bangi, Malaysia [38]. In comparison to conventional paraffin wax PCMs, it explores the use of novel sheep fat and sheep fat+CuO nanoparticles as phase change materials (PCMs) in photovoltaic (PV) modules, demonstrating enhanced cooling performance and higher power generation efficiency [39]. With respect to energy and energy efficiency, cost-effectiveness, and CO2 reduction, the Plate Heat Sink (PHS) condenser performs better than other designs, according to this study that looks at the impact of passive condenser designs on solar distiller performance [40].

II. EXPERIMENTAL SETUP

An experimental setup was designed and built at JIS College of Engineering, Kalyani, West Bengal, India (26.1332°N, 91.6214°E), and experiments were carried out for three months, in April, May, and June, in order to ascertain the impact of PCM cooling system on PV performance. The next subsections provide a description of the experimental setup's design elements as well as experimental measurements.

A. Design of Test Setup

The experimental setup was established at JIS College of Engineering, Kalyani, West Bengal, India (26.1332°N, 91.6214°E). Two identical PV modules, each rated at 20 W, were mounted at a 26° tilt to align with the local latitude. One module served as the control, while the other was integrated with an aluminum enclosure filled with approximately 500 grams of paraffin wax (RT-42) beneath the panel. Table 1 outlines the specifications of the PV panels, and Table 2 provides the thermophysical properties of the paraffin wax used. The experimental period spanned April to June, encompassing arying solar and thermal conditions typical of the Indian summer.

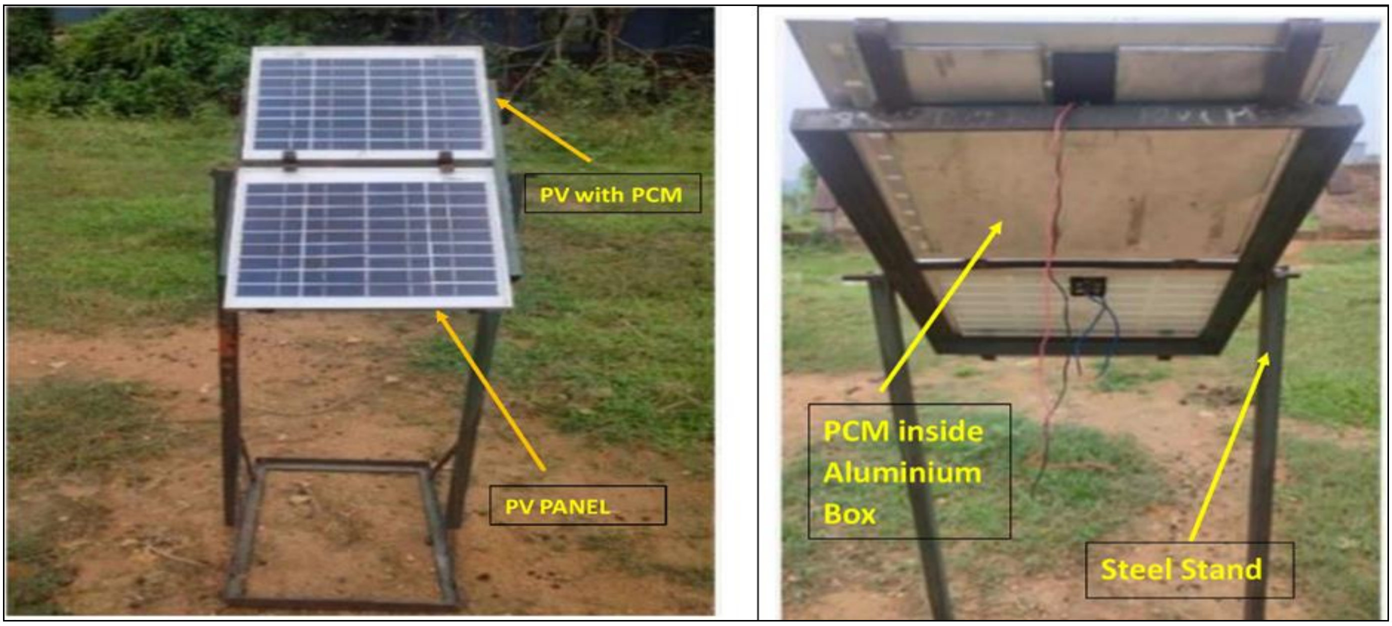

Fig 1: A Photograph of the Experimental Setup

Table 1: Specification of the PV Module

No. of Solar Panel Used	**2**
Rated Power (Pmax)	20 Wp
Rated Voltage (Vmp)	19.6 V
Rated Current (Imp)	0.59 A
Open Circuit Voltage (V_{oc})	21.6 V
Short Circuit Current (I_{sc})	0.65 A
Fill factor (FF)	0.823
Panel length	0.077m
Panel width	0.024m
Area of the Panel	0.066528m^2

Table 2: Thermo-Physical Properties of Paraffin Wax

Property	**Values**
Melting Temperature (T_m) [ºC]	53.7
Specific heat of solid phase (C_{ps}) [kJ/kg.K]	2.0
Specific heat of liquid phase (C_{pf}) [kJ/kg.K]	2.15
Thermal Conductivity of solid phase (k_s) [W/m.K]	0.24
Thermal Conductivity of liquid phase (k_f) [W/m.K]	0.22
Density of solid phase (ρ_s) [kg/m^3]	910
Density of liquid phase (ρ_f) [kg/m^3]	790
Latent heat of fusion [kJ/kg]	190

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B. Data Collection

Measurements were conducted daily between 9:00 a.m. and 3:00 p.m. Instrumentation included digital multimeters to capture voltage and current, and infrared thermometers to monitor surface temperatures. Data recorded included open circuit voltage (Voc), short circuit current (Isc), and corresponding temperature profiles.

III. RESULTS AND DISCUSSIONS

The experimental outcomes following the PCM addition to the PV system are explained in this section. On all days in April, May, and June, the experiments were carried out, and the average value of every parameter that was measured has been provided.

A. Environmental Parameters

Figures 2. and 3. show, respectively, how the solar intensity and ambient temperature changed during the course of the experiment days. Solar radiation peaked at 776 W/m², 806 W/m², and 743 W/m² in April, May, and June, respectively. Ambient temperatures followed a similar trend, reaching maximums of 33°C, 37°C, and 38°C across the same months.

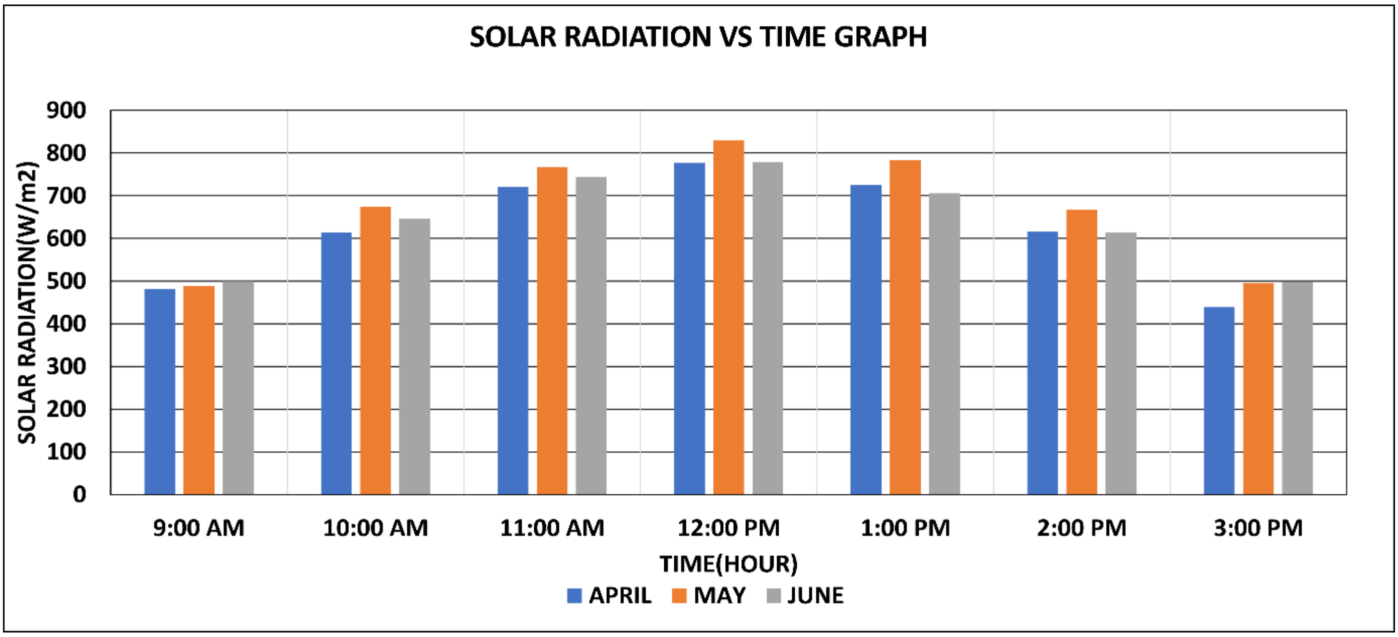

Fig 2: Temporal Changes in Solar Radiation Recorded Across the Test Duration

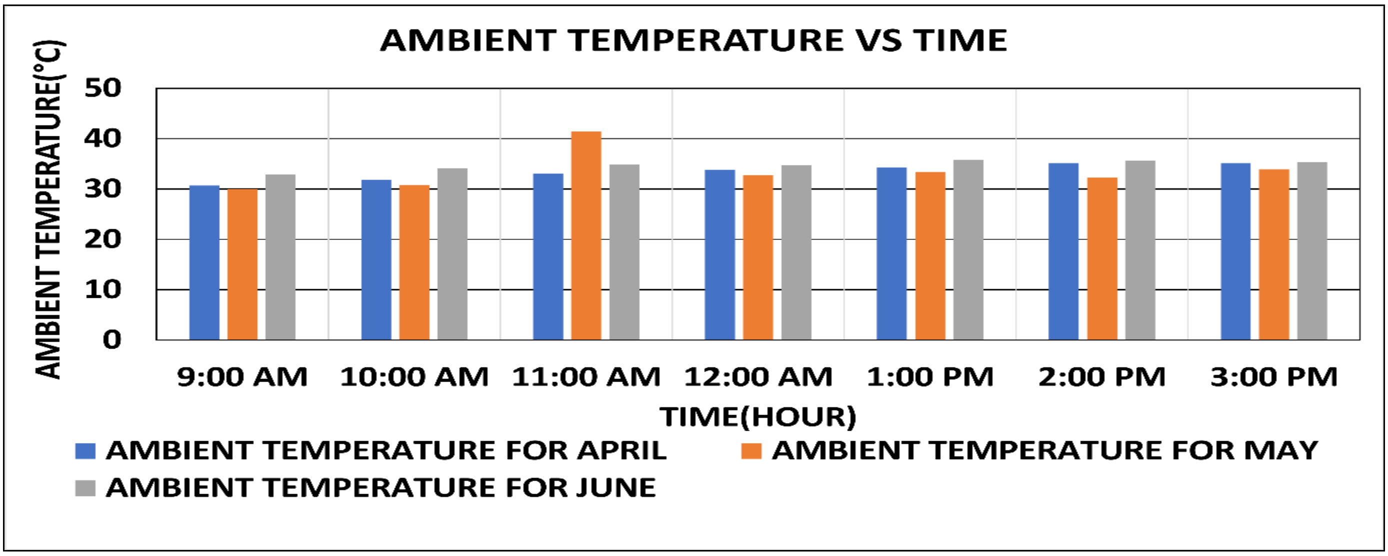

Fig 3: Observed Changes in Ambient Temperature Across the Duration of the Experiments

B. Thermal Performance

Figure 4. shows the changes in solar cell temperatures for PV and PV-PCM setups in the months of April, May, and June. The PCM-cooled panel exhibited a consistent reduction in surface temperature compared to the control. Peak temperatures for the control panel exceeded 48°C, whereas the PCM-integrated panel remained below 41°C, demonstrating effective thermal regulation. This temperature moderation is attributed to the latent heat absorption capability of the paraffin wax.

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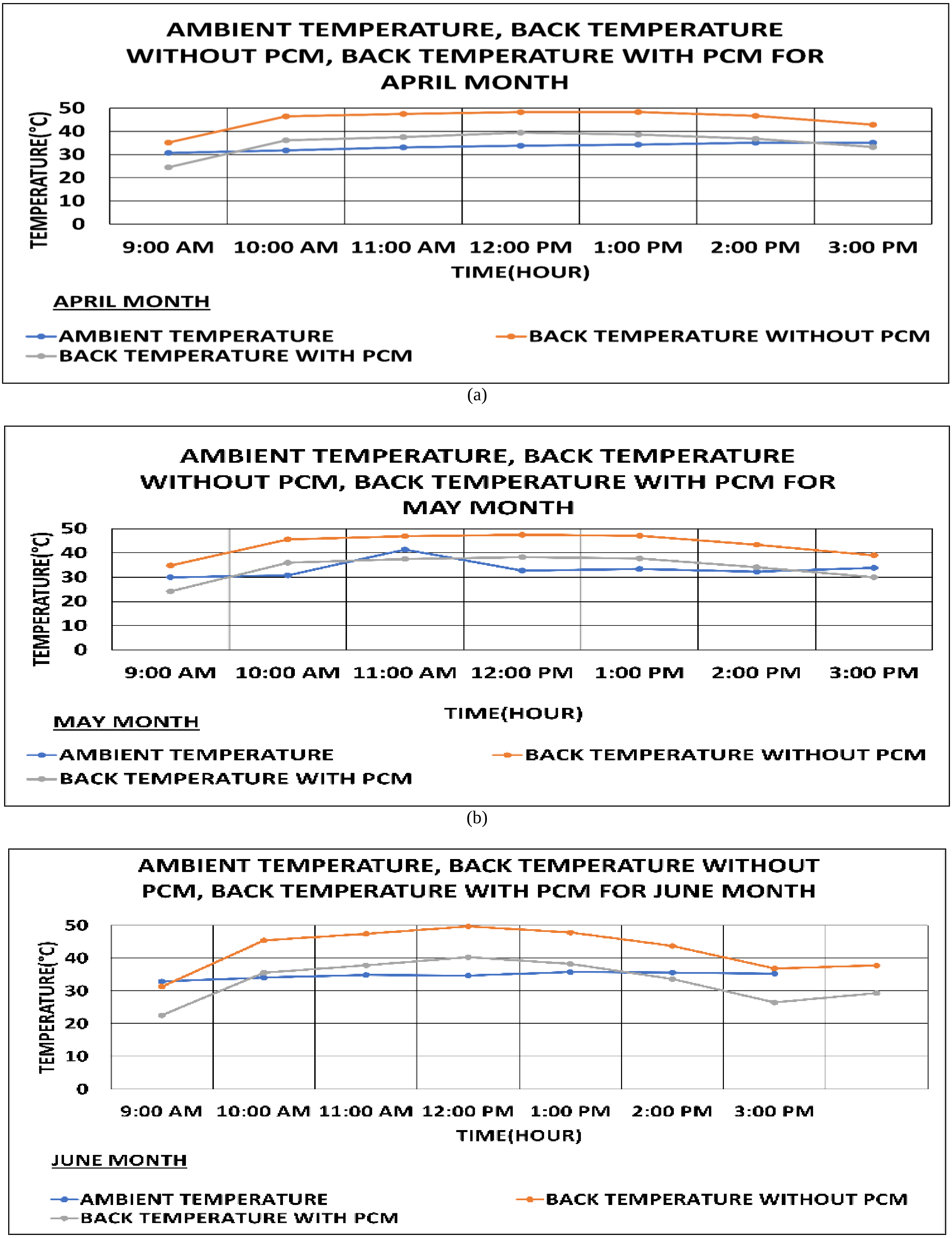

(c)

Fig 4: Temperature Trends of Solar Cells in Standard and PCM-Integrated PV Configurations During (a) April, (b) May, and (c) June

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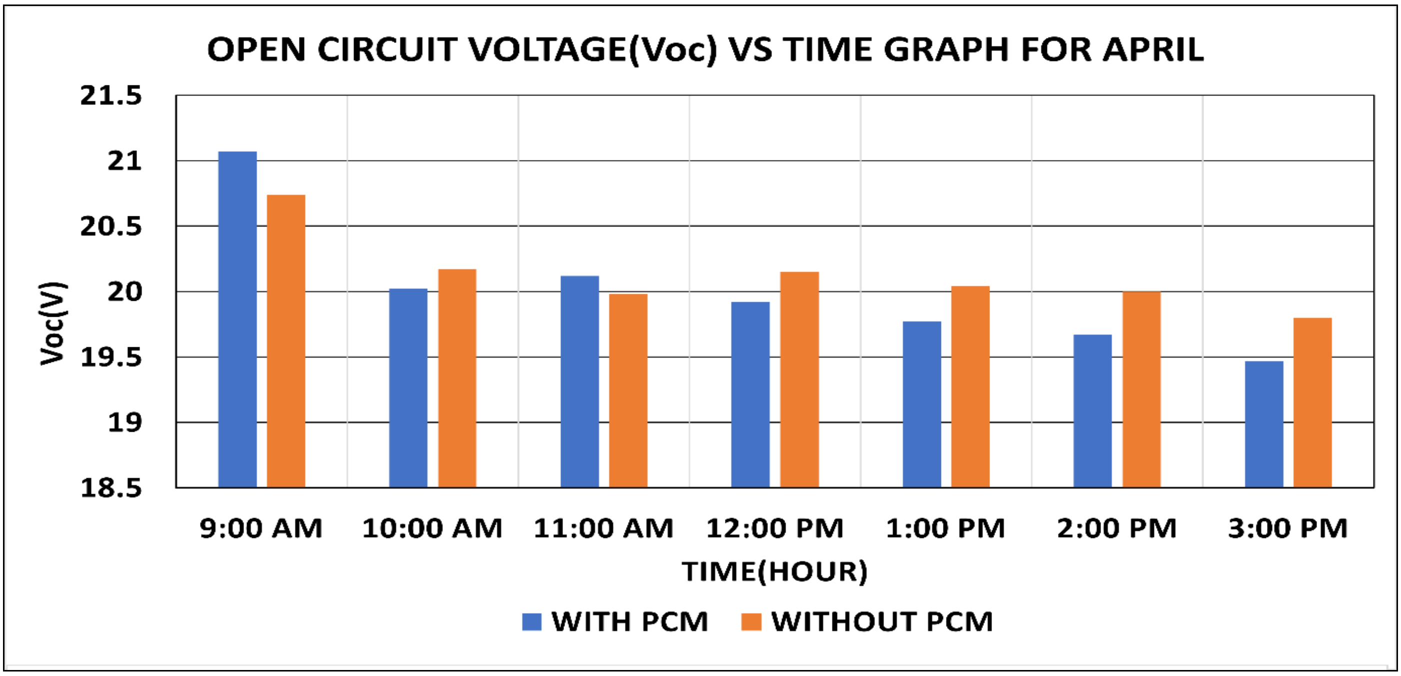
C. Electrical Performance

Voc and Power Output: The PCM-cooled system displayed higher open-circuit voltages during peak radiation hours due to lower cell temperatures. Power output improvements were recorded at 9.8%, 13.1%, and 10.3% for April, May, and June, respectively. Efficiency: Efficiency gains followed the same trend. The PCM-enhanced system achieved peak efficiencies of 27%, 43.1%, and 33% for the respective months, compared to 23.4%, 38.1%, and 30.2% for the control panel.

➢ *Open-Circuit Voltage*

Figure 5. displays the Voc values measured for both systems. The Voc of the PV-PCM setup is found to be greater than the PV set up until solar noon, or 12 p.m., at which point, as the radiation decreases, the Voc of the conventional setup surpasses the PV-PCM setup because heat is released from the PCM into the PV panel, raising its temperature and causing a rapid rise in reverse saturation current and a subsequent drop in cell voltage.



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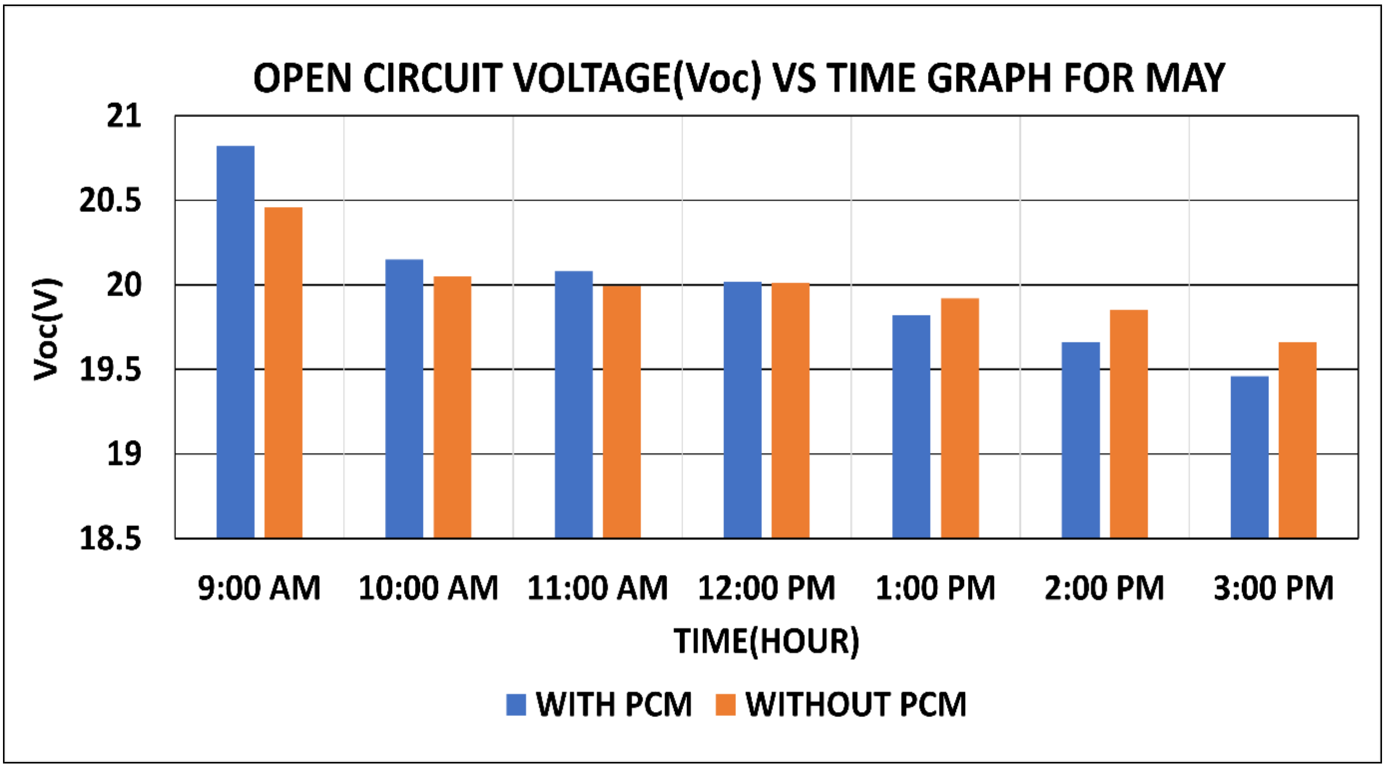

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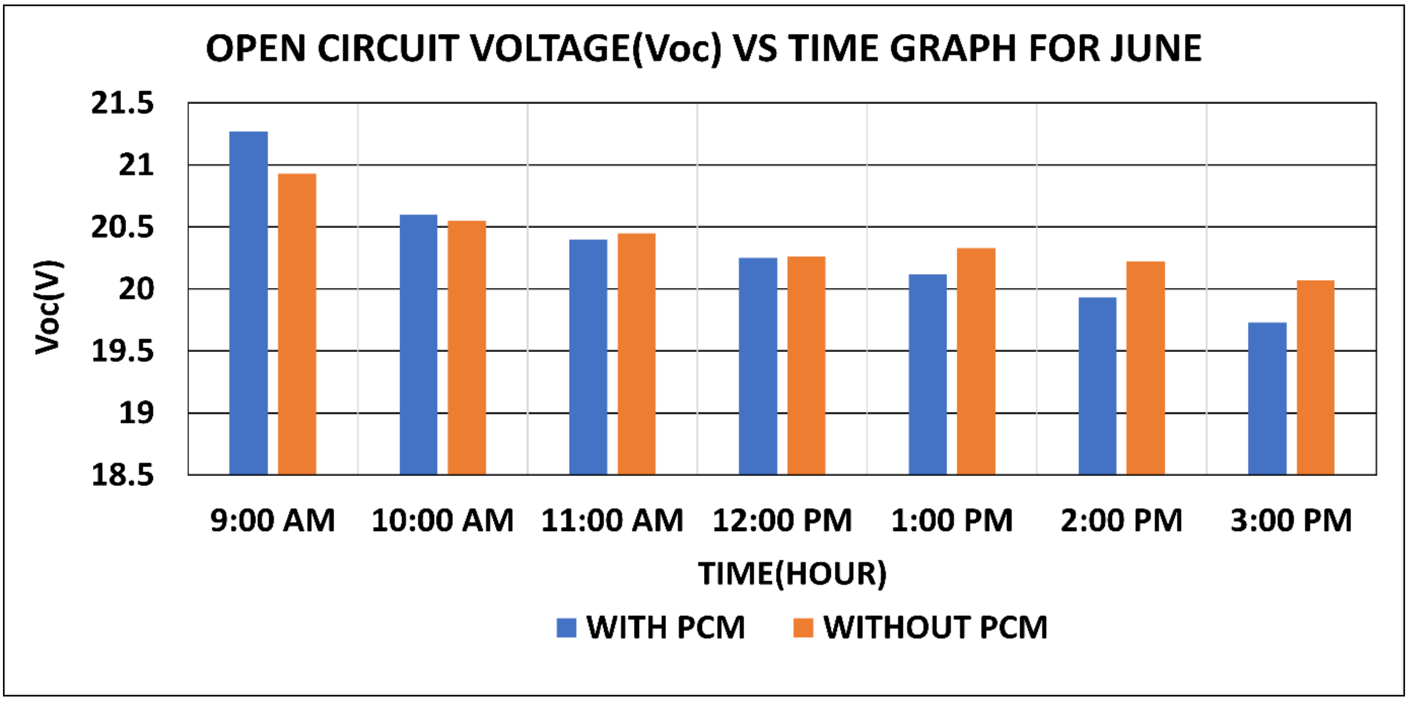
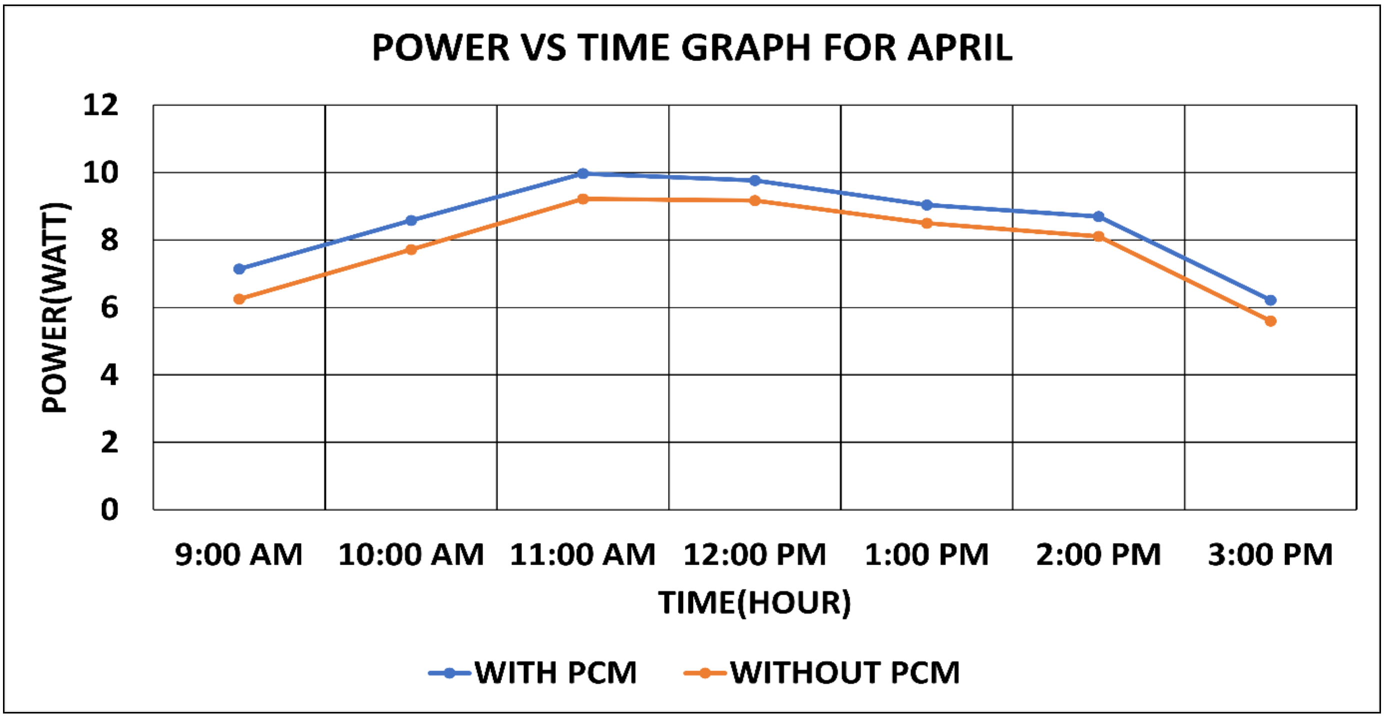


(c)

Fig 5: Monthly Analysis of Open-Circuit Voltage (Voc) for Conventional and PCM-Cooled PV Modules: (a) April, (b) May, (c) June

- *Power Output*

Figure 6. displays the power output produced by both systems throughout the course of the day. From the start of the experiment until solar noon, the generated power progressively grew and finally decreased. However, it was noted that the PV-PCM setup's output power was greater than the traditional PV system's. In April, May, and June, respectively, the generated power of the PV integrated with PCM was 9.8%, 13.1%, and 10.3% higher than the conventional model. The summer season in India starts in April and, depending on the location, lasts until June or July. The month of May often sees the maximum temperatures, and when the monsoon season begins in June, the temperature gradually begins to decline.



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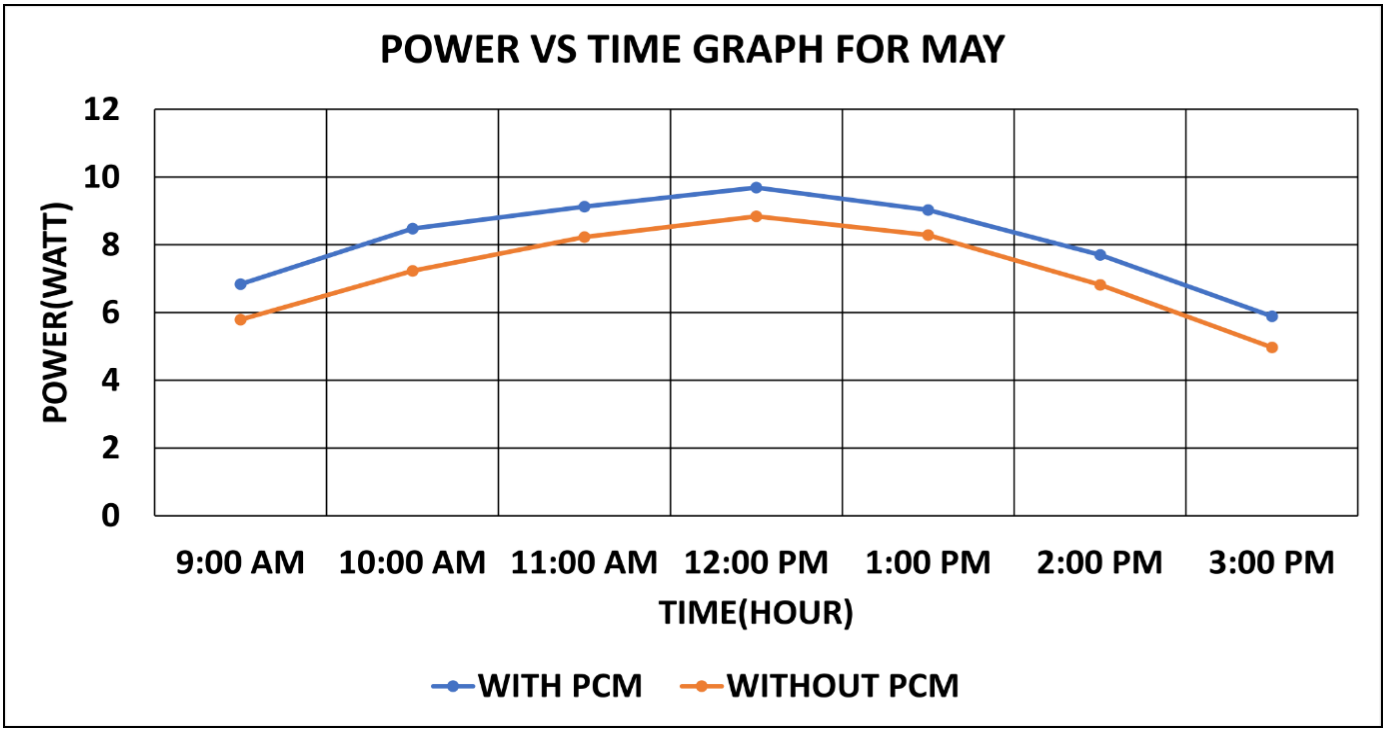

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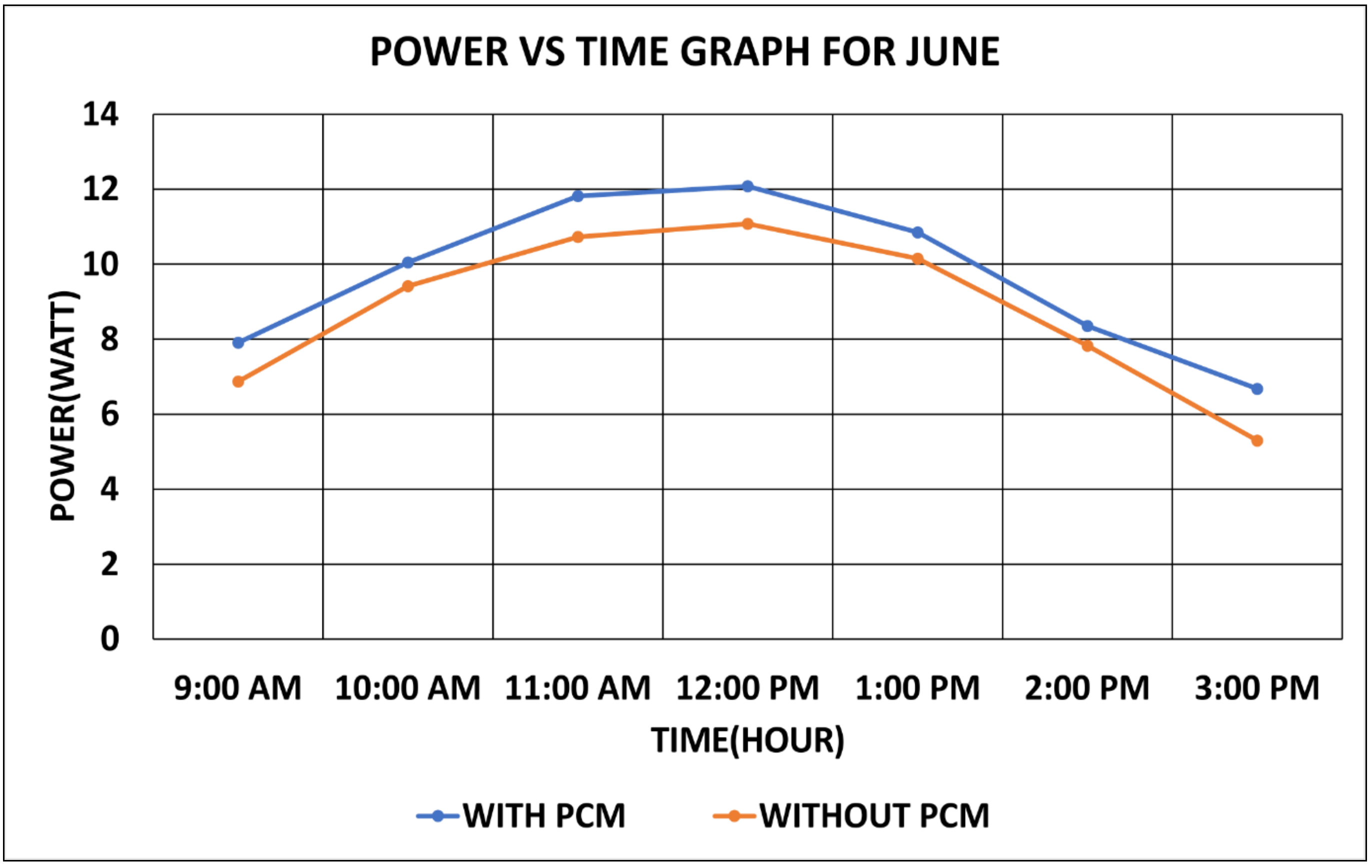

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Fig 6: Month-Wise Variation in Power Output for Conventional and PCM-Integrated PV Panels: (a) April, (b) May, and (c) June

➢ *Efficiency*

The growth of efficiency of both the systems, PV and PV-PCM, during the experiment, is presented in Fig.7. The results indicated that the efficiency of PV-PCM was greater than traditional PV. It was seen that the highest efficiency produced for conventional PV was 23.4%, 38.1%, and 30.2%inApril, May, and June, respectively, while the corresponding value for PV-PCM was 27%, 43.1%, and 33%, respectively, leading to an increase in overall efficiency by 2.5%.

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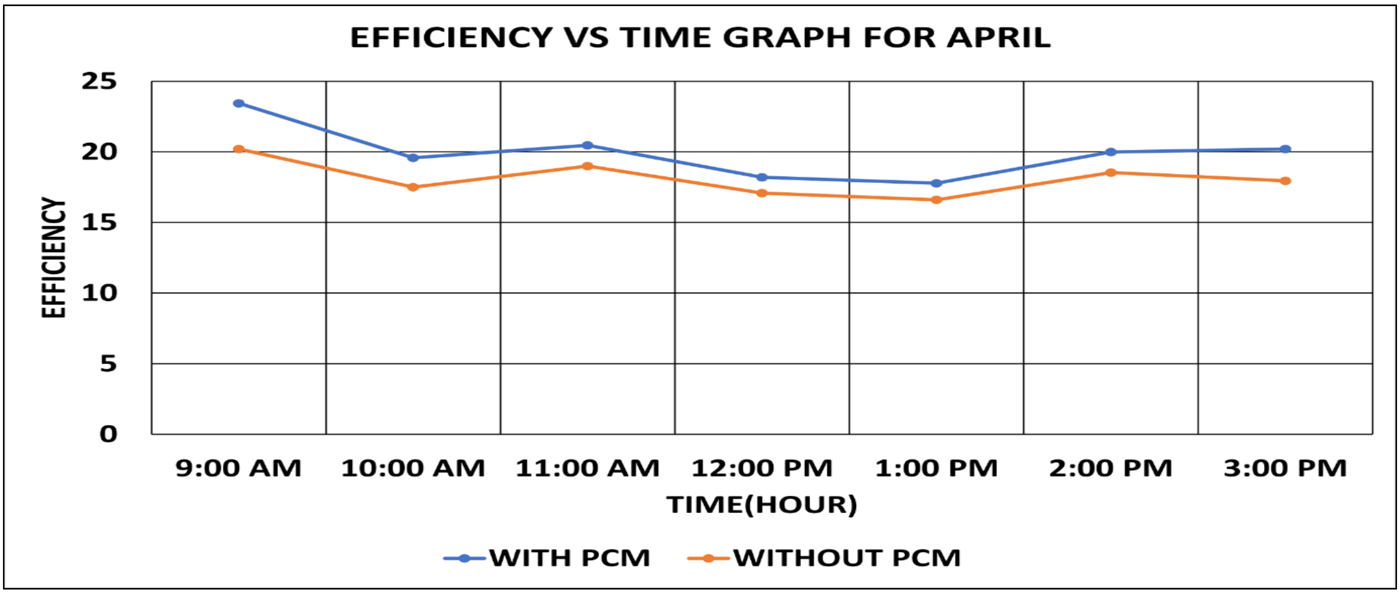

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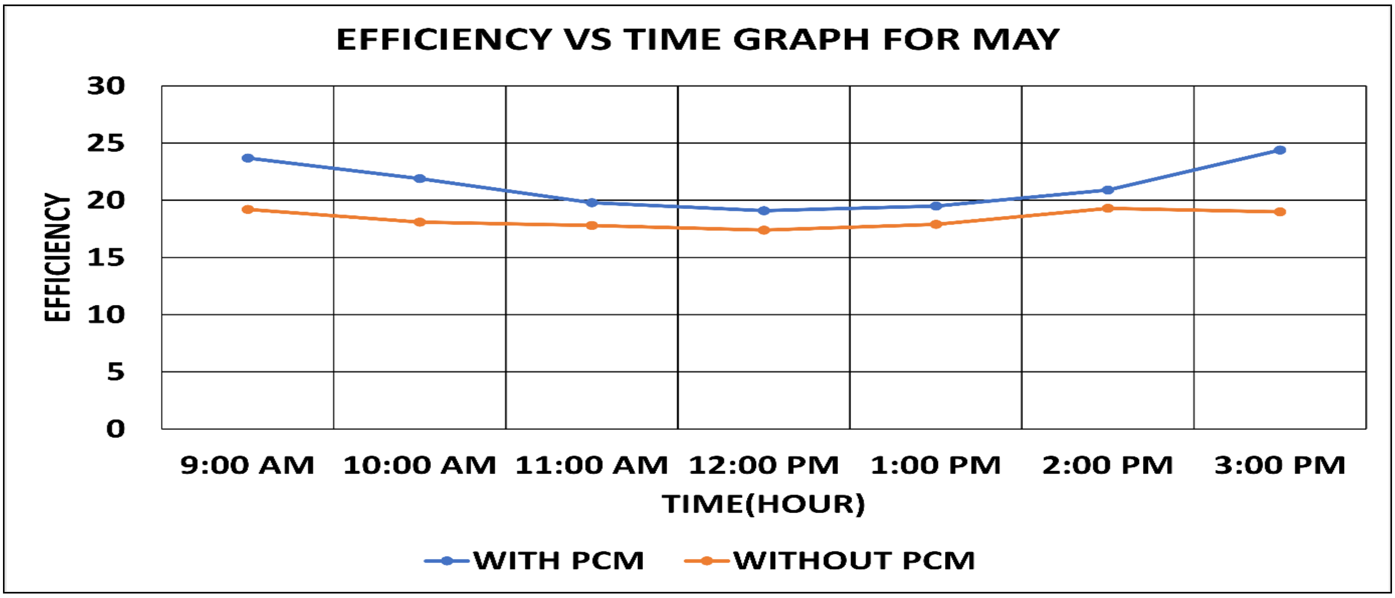

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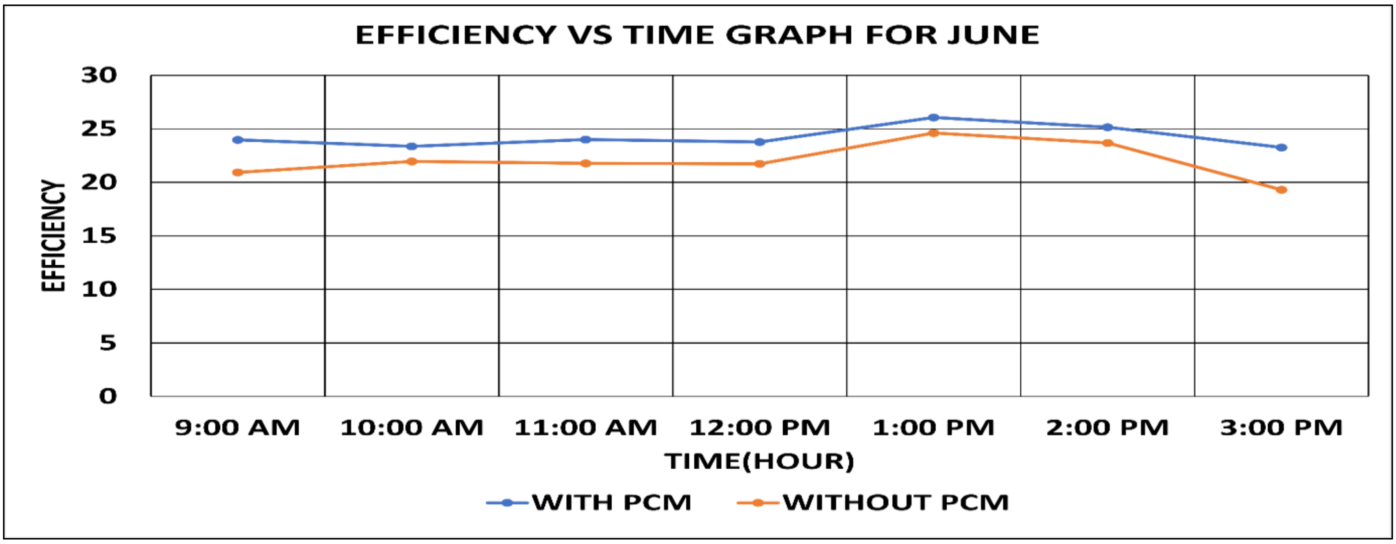

(c)

Fig 7: Efficiency Comparison of PV and PCM-Integrated PV Systems Over the Months of (a) April, (b) May, and (c) June.

IV. CONCLUSIONS

This study confirms that incorporating paraffin-based PCM beneath PV modules significantly enhances performance by mitigating thermal stress. The passive cooling effect reduces the surface temperature, stabilizes output voltage, and improves energy conversion efficiency. A peak improvement of over 13% in power generation was observed, indicating strong potential for PCM-based thermal regulation in solar installations, particularly in hot climates. Future work may explore economic viability, long-term PCM stability, and performance under varying weather patterns to support large-scale deployment.

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