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Performance evaluation of a photovoltaic system with phase change material in Guwahati

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ABSTRACT

Recently, there has been a lot of interest in solar photovoltaic (PV) technology as a clean and renewable energy source. The operating temperature of PV modules significantly impacts their performance; as the temperature rises, the modules perform worse. The phase change material (PCM) paraffin wax has been used to cool a PV system passively. The experiment was carried out during summer over three months, viz. April, May, and June when relative humidity was around 80.75% to 86.5% with two identical 20-watt PV panels in Guwahati, India (26.1332° North and 91.6214° East). One panel was coated with PCM, while the other panel functioned as a point of reference. The study reveals an impressive result: the output power produced by the system with PCM was 9.8%, 13.1%, and 10.3% greater than the reference PV, while the surface temperature had been lowered by 21.6%, 26.2%, and 30.6% in the three respective months. High humidity delays the release of latent heat of paraffin wax and hence improves its thermal conductivity. This study adds to the continuing efforts to promote sustainable energy solutions and creates new opportunities to enhance the performance of PV systems.

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1. INTRODUCTION

An essential component of a nation's economic growth is the energy industry. Population growth has raised energy demand, which has led to widespread use of fossil fuels and environmental damage. Worldwide demand for renewable energy is rising because of the depletion of fossil resources. In India, solar energy seems to be a potential renewable energy for bridging the gap between demand and supply. As temperature affects panel performance, cooling techniques are being investigated for improved PV output characteristics [1]. Several environmental conditions, including humidity, dust, and temperature, influence the efficiency and performance of solar photovoltaic (PV) cells. It has been observed that increases in dust quantity and high relative humidity are associated with a significant reduction in PV cell output [2]. Research examining the effects of humidity on PV panel performance has indicated that a 50.15% increase in humidity is linked to a 34.22% reduction in power output, while humidity levels rising from 65.40% to 98.20% are associated with an 11.40% decrease in panel temperature [3]. Furthermore, it has been demonstrated that the output of solar PV systems is significantly affected by relative humidity, with increases in humidity leading to decreases in current, voltage, and power, illustrating the critical link between relative humidity and PV performance [4]. The efficiency of PV panels drops as they heat up from extended exposure to sunshine. Optimizing PV performance requires thermal control, and using phase change materials (PCMs) is one promising strategy. The ability of PCM to absorb and release heat during phase transitions makes maintaining PV panels operating at optimal temperatures possible. PCMs are considered ideal for latent thermal energy storage (LTES) applications due to their capacity to store and release large amounts of energy at a constant temperature, which renders them highly compatible with variable renewable energy sources [5]. Paraffin wax-based PCMs, particularly those enhanced with nano-additives such as multi-walled carbon nanotubes (MWCNTs), have been shown to offer high thermal storage efficiency and stability, making them well-suited for thermal energy storage systems. The effectiveness of these materials has been confirmed through analyses such as SEM, EDX, FTIR, and TGA, which have revealed high thermal conductivity, chemical compatibility, and stability, affirming their suitability for solar thermal applications [6]. It has been found that incorporating PCMs and metal foams to store and regulate energy in colder climates has improved PV performance [7]. Innovative methods like front cooling with water and active cell surface cooling significantly enhance solar PV panels' efficiency [8]. I mmersing solar PV panels in water to a depth of 20 mm raised efficiency to 15.54%, providing better cooling and potential improvements in energy output [9]. The study looks into how different cooling techniques, such as water immersion and active procedures, might improve the efficiency of PV panels. It shows that water immersion, reflectors, and heat sinks can increase efficiency [10]. Active cooling techniques for PV panels, including water spraying, can yield significant efficiency improvements under several situations by lowering temperatures, improving power output, and reducing reflection losses [11]. Cooling techniques such as applying PCMs to reduce heat-related losses are essential to improving the output and efficiency of solar panels [12]. It is possible to sustainably produce enhanced per capita energy by enhancing the PV cell efficiency using various cooling techniques [11].

Paraffin wax is considered a superior PCM because of its great stability and efficiency in thermal storage, especially when combined with nano-additives such as MWCNTs. Applying metal foams with excellent thermal conductivity improves heat transmission in PCMs. Different kinds of metal foam are integrated with PCMs to enhance the efficiency of energy storage systems [13]. Many simulation works are done using gambit and fluent for comprehensive analysis regarding applications of paraffin wax, sodium acetate tri-hydrate, and phenolphthalein in engine coolant heat absorption. These applications use conduction and convection in latent heat storage [14]. To maximize solar energy utilization, phase transitions are crucial for effective latent heat thermal energy storage (LHES). Materials such as salt hydrates, paraffin, and non-paraffin organics have been investigated for dense temperature storage in heating, cooling, and other applications, such as eutectics of inorganic and organic compounds [15]. It has been observed that Malaysia's environment is ideal for solar energy use because of the country's annual average solar radiation of 4.21–5.56 kWh/m². Still, excessive radiation levels cause PV panels to overheat, which could reduce their efficiency [16]. PCM cooling devices have been shown in outdoor studies to have the potential to increase solar panel efficiency; nevertheless, panel temperature increased owing to increased irradiation levels [10]. Solar energy generation is prioritized in Nigeria because of its constant sunshine, and cooling techniques like heat sinks and water spraying have shown promise in preserving PV module efficiency even in the face of temperature rises brought on by exposure to sunlight [17]. To improve PV system performance, including less cell deterioration and increased thermal and electrical efficiency, a variety of cooling strategies need to be explored [18]. Incorporation of PCMs into domestic heating systems, examining how they might reduce emissions, lessen dependency on fossil fuels, and contribute to a more environmentally friendly future [19]. A year-long evaluation in the UAE highlighted the importance of selecting the ideal PCM type and melting point to optimize PV power output [20]. Additionally, the effective storage of surplus solar energy collected during the day by paraffin wax PCMs has enabled the availability of extended energy at night. These materials' significant charging and prolonged discharge durations have been reinforced as reliable for renewable energy applications [21]. Adding PCMs RT35 and RT35HC to hollow clay bricks improved indoor cooling by 13%. It increased heating energy savings by 9.5%, according to a study done in Jeddah, Saudi Arabia. It was reported that PCM RT35 saved 0.533 kWh per wall, while PCM RT35HC saved 0.8 kWh, potentially reducing HVAC energy consumption by up to 146 kWh/m² annually [22].

However, it has been found that the performance of solar PV systems is significantly affected by relative humidity, which is linked to reduced power output and efficiency and decreased current and voltage levels [23]. Although humidity has been found to impact PV output negatively, it also improves the output characteristics of PV by increasing the thermal conductivity of paraffin wax and delaying its phase transition, which delays the release of latent heat. This increased thermal conductivity is considered vital, as it enables temperature fluctuations to be managed more efficiently, preventing excessively high temperatures from being reached by the solar cells, which can degrade their performance [24].

The above literature review shows that only a few experimental works have been carried out to analyse the output characteristics of PV panels by incorporating PCM and mainly focusing on the effect of temperature on PCM. However, limited research investigates the impact of relative humidity on PCM. The primary goal of this work is to examine the effect of employing PCM as a passive cooling material for PV systems in humid subtropical climates such as Guwahati town. The experiments were conducted in a summertime environment: two panels, one with PCM and the other without, made up the setup. The PV panel's temperature distribution and several other electrical data were depicted during the summer in April, May, and June. This study advances our knowledge of how temperature and relative humidity affect the PCM used in PV systems.

2. EXPERIMENTAL SETUP

To determine the effect of the PCM cooling system on PV performance, an experimental setup was designed and constructed at Girijananda Chowdhury University, Guwahati, Assam, India, located at (26.1332° North and 91.6214° East). Experiments were conducted for three months: April, May, and June. The following subsections describe the experimental setup's design elements as well as experimental measurements.

2.1. Design of test setup

In this investigation, the effects of adding PCM to PV modules on their performance were investigated through outdoor testing as hown in Figure 1. Two distinct PV panel designs, each with a 20 W rating, were employed in this configuration: a conventional PV system and a PV system with PCM that used an aluminum container. Figure 1(a) depicts the experimental setup. Figure 1(b) is multimeter, and Figure 1(c) is infrared thermometer. While similar weather circumstances continued, the electrical and thermal capacities of the two sets were computed in real-time. The PV module specifications are outlined in Table 1. The PCM in this arrangement is RT 42 paraffin because of its advantageous thermal and physical properties, including availability, affordability, lifespan, non-corrosiveness, and relatively high enthalpy of fusion compared to other PCM kinds. Table 2 provides additional data about the specified PCM's characteristics. Below the PV module, an aluminum container measuring 0.295×0.266×0.1 m with a 1.37 mm thickness was integrated. The paraffin wax RT-42 PCM was stored within for passive cooling. The container is filled with 500 grams of paraffin wax. Both panels are positioned facing south on a platform at a 26° inclination angle based on Guwahati city's latitude to receive the maximum amount of solar insolation, which has been taken from the regional meteorological center [25].

(a)

(b) (c)

Figure 1. The effects of adding PCM to PV modules on their performance (a) a photograph of the experimental setup, (b) multimeter, and (c) infrared thermometer

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

2.2. Experimental measurements

Two identical 20-watt PV panels were used; one was waxed, while the other served as the standard. The goal was to determine how paraffin wax affected the panel's functionality. A digital multimeter UNI-T UT33D as shown in Figure 1(b). was used to measure the Isc and Voc for panels at an interval of one hour from 9 a.m. to 3 p.m. every day for three months, *viz* April, May, and June. An infrared thermometer, Benetech GM320, as shown in Figure 1(c) was used to record the panel temperatures at the front and rear. The solar radiation, relative humidity, and ambient temperature data were collected from the regional meteorological center [25]. The power output and the efficiency of the set up were then calculated integrating the humidity derating factor in the efficiency calculations. The information acquired during this period was beneficial in understanding how the temperature responsiveness and efficiency of the panel were affected by the paraffin wax coating as wellthe relative humidity.

2.3. Humidity factor

Humidity can heavily impact efficiency by lowering it through scattering solar radiation and causing condensation, which reduces the amount of sunlight reaching the cell. The calculation of the efficiency of the PV cell under humidity is done by introducing a derating factor D_h given in (1) as mentioned by Lawrence [25] y, which depends on the relative humidity RH as follows:

$$D_h = 1 - \frac{RH - Href}{Hmax - Href} \quad (1)$$

Where:
$D_h(H)$ = humidity derating factor, which increases with relative humidity.
RH = relative humidity.
Hmax = maximum humidity.
Href= humidity when output id optimal.

$$\eta PV(H) = \eta PV,0 \times (1 - Dh(H)) \quad (2)$$

Where:
ηPV(H) = PV efficiency at a given humidity.
ηPV,0 = baseline PV efficiency under standard conditions.

3. RESULTS AND DISCUSSION

This section presents the experimental results, analysis, and comparison of PV-PCM with PV. Theexperiment was carried out in each day from April through June of 2023 and the average values of the various measured parameters have been presented.

3.1. Weather data

Guwahati city in the Indian state of Assam has a humid subtropical climate. Weather data has significant implications for the measured parameters. Hence, the weather data on the days when the experiments were carried out has been presented. Figures 2-4 illustrate the changes in ambient temperature, sun intensity, and relative humidity throughout the experiment days. Between 60% and 88% is the range of relative humidity. In April, May, and June, the most outstanding significant sun intensity values were 776 W/m2, 806 W/m2, and 743 W/m2, respectively, as shown in Figure 3. Furthermore, as illustrated in Figure 4, the maximum outside temperature in April, May, and June was 33 °C, 37 °C, and 38 °C. The data were collected from the regional meteorological center [25].

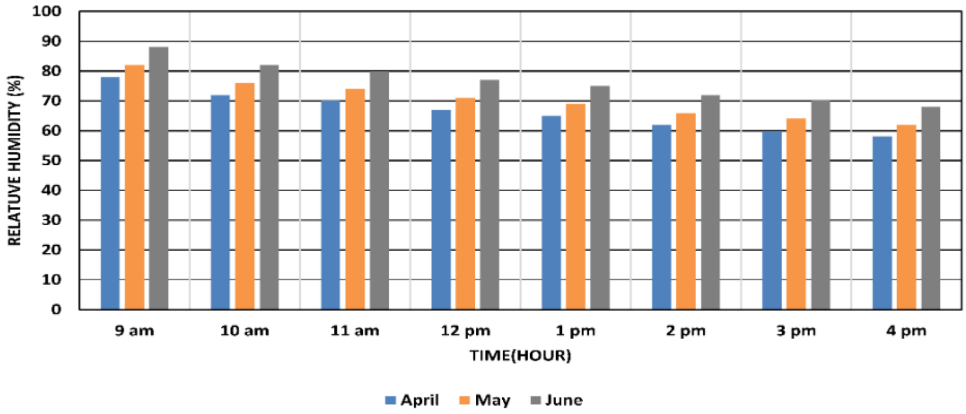

Figure 2. Relative humidity vs time

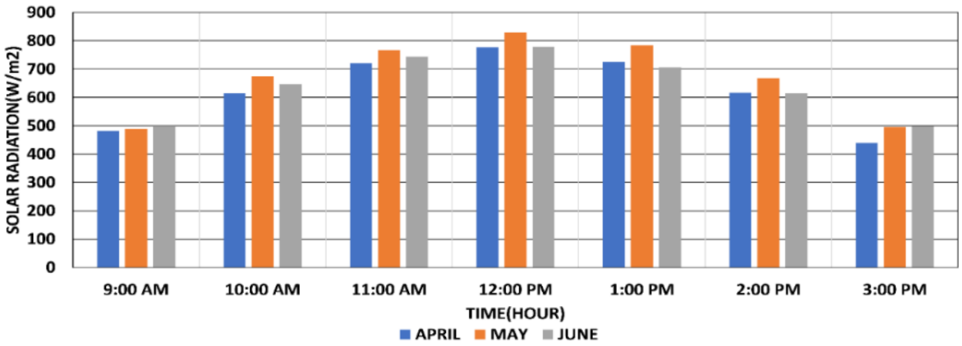

Figure 3. Solar radiation vs time

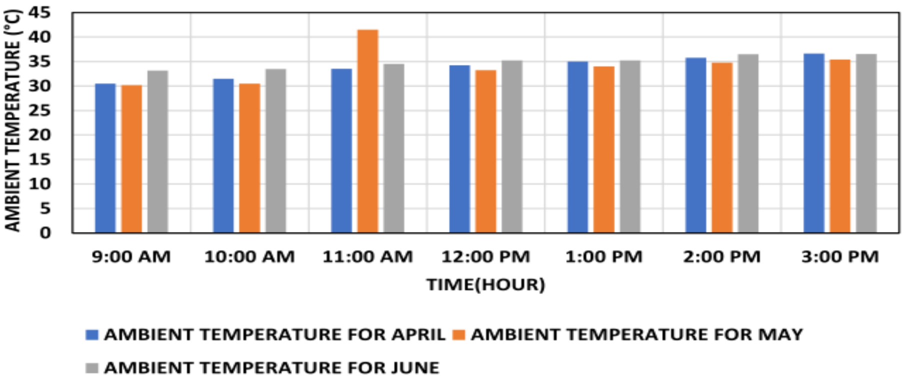

Figure 4. Ambient temperature vs time

3.2. Thermal performance
3.2.1. PV temperatures

Optimizing cell temperature, which is impacted by the rise in module temperature, is crucial to maximize PV system performance as every degree rise in cell temperature decreases the efficiency by 0.5%. Moreover, prolonged exposure to high temperatures can lead to thermal degradation, reducing the life span of PV cells [26]. Figures 5-7. show the modulel temperature changes for PV and PV-PCM setups in the said months. The most incredible average surface temperatures of the PV-PCM system were 39.4 ºC, 38.2 ºC, and 40.3 ºC, respectively, for April, May, and June, while the maximum surface temperatures of the standard PV system were 48.3 ºC, 47.5 ºC, and 49.1 ºC. In all these three months, the average temperature of the solar cell was successfully lowered by 26.13%. This is a very remarkable outcome as the use of PCM has lowered temeperatures in non humid places only by an average of 8.2% [7]. The PV-PCM system's surface temperature stayed below traditional PV's because of PCM's capacity to dissipate heat and also because of the high humidity of the region.

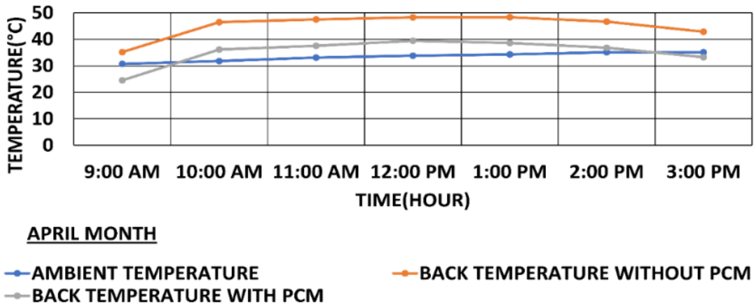

Figure 5. Ambient temperature, back temperature without PCM, back temperature with PCM for April month

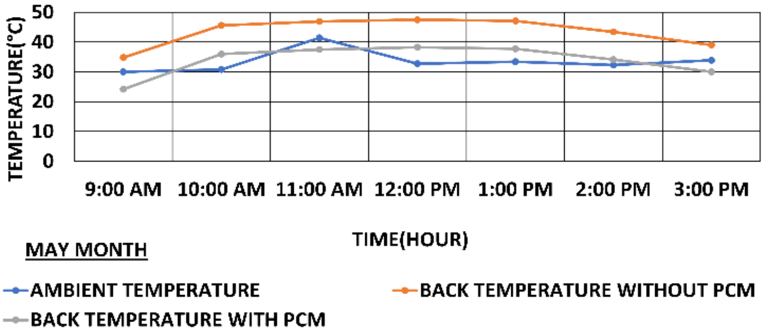

Figure 6. Ambient temperature, back temperature without PCM, back temperature with PCM for May month

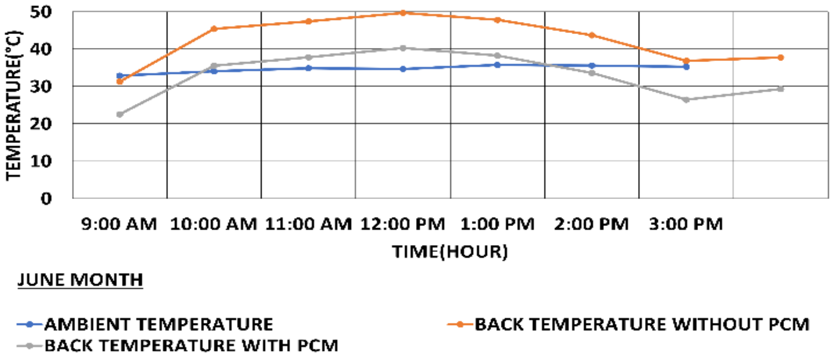

Figure 7. Ambient temperature, back temperature without PCM, back temperature with PCM for June month

3.3. Electrical performance

The two most crucial metrics for assessing the PV system's electrical performance are short circuit current (ISC) and open circuit voltage (Voc). The electrical performance of a PV panel is determined by the temperature of the solar cell and the amount of incident solar insolation. Variations in these variables influence the Voc and the Isc for PV system design. The temperature increase causes the band gap to decrease, which raises the Isc somewhat. Only VOC for both systems is provided in this part, as presented in the figures below. The variation in their ISC is not very significant. A comparison of their power production and efficiency is subsequently carried out.

3.3.1. Open-circuit voltage

Relative humidity and an increase in temperature decrease the Voc of PV. Still, adding paraffin wax reduces this effect's magnitude as humidity enhances its thermal conductivity [27]. Relative humidity has a negligible impact on Voc as compared to temperature. As temperature increases, band gap energy increases, which leads to a decrease in Voc. Figure 8 displays the Voc values measured for both systems. It has been discovered that the PV-PCM setup's Voc is higher than the PV setup's until solar noon or noon. 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.

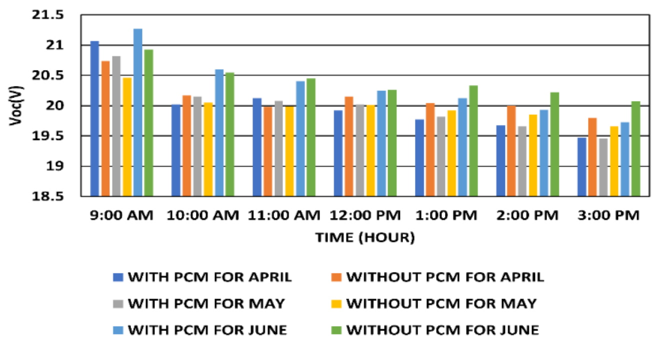

Figure 8. Open circuit voltage(Voc) vs time graph

3.3.2. Power output

It has been found that with an increase in humidity level by 50.15% the power output decreased by 34.22% [3]. Figure 9 depicts 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. It was observed that the output power of the PV-PCM configuration was higher than that of the conventional PV system. The PV integrated with PCM's average power output was 9.8%, 13.1%, and 10.3% higher than the conventional model in April, May, and June, respectively. 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.

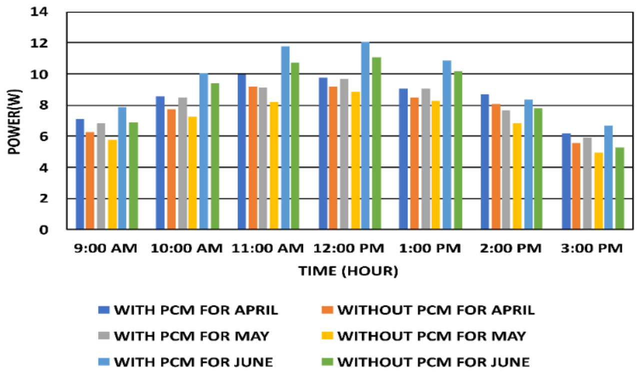

Figure 9. Power vs time graph

3.3.3. Efficiency

Relative humidity is typically observed to have a detrimental effect on the output of PV systems, as increased moisture can create an insulating layer on the solar panels [28]. The efficiency calculations has been done by incorporating the humidity derating factor as given (2). It is well recognized that this insulation lowers the solar cells' efficiency by impeding their capacity to disperse heat, which is essential for optimum operation. As temperatures rise, a decline in the efficiency of conventional PV systems is noted, leading to lower energy production. However, notable alterations are pointed out in systems that use PCM. The PCM's thermal conductivity can be improved by humidity, which makes it possible for heat to be absorbed, stored, and released more efficiently than other materials. Figure 10 shows the increase in efficiency of PV and PV-PCM systems during the trial. The findings showed that PV-PCM was more efficient than conventional PV. In April, May, and June, the maximum efficiency generated by traditional PV was 20.2%, 18.68%, and 23.68%, respectively. In contrast, the comparable figure for PV-PCM was 23.44%, 23.7%, and 25.15%, respectively, resulting in a 2.5% increase in overall efficiency.

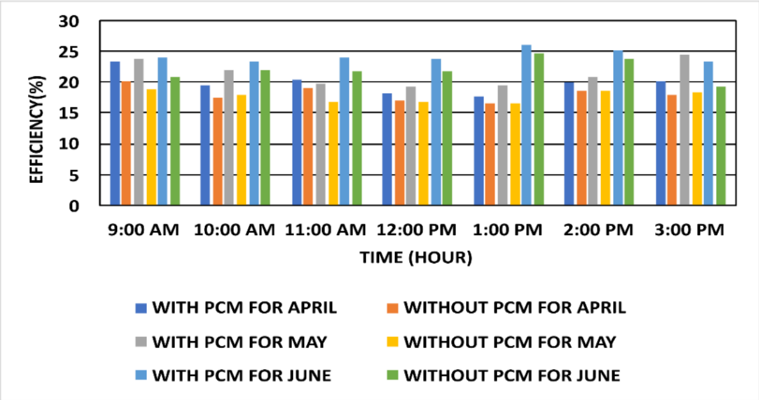

Figure 10. Efficiency vs time graph

4. CONCLUSION

In the present work, an experiment was carried out in Guwahati, India, throughout the summer to analyze the viability of improving the PV system's performance by combining it with PCM. Two systems were the subject of experiments: one had a PV integrated with PCM in an aluminum container, and the other was a conventional system that included only PV. For April, May, and June, the temperature distribution on the PV surface, the Voc, the output power produced, and the efficiency of both systems have been provided. The system's temperature has been successfully lowered significantly due to PCM usage. This counterintuitive phenomenon is illustrated by the integration of PCM, which mitigates the adverse effects of high temperatures and leverages humidity to enhance thermal performance. As a result, the overall efficiency of PV systems that utilize PCM is achieved, despite the general understanding that increased humidity negatively affects traditional solar panel performance. This synergy between humidity and PCM thermal properties underscores the potential for integrating PCM in solar energy systems, particularly in regions experiencing high ambient temperatures and humidity levels. By effectively managing heat, PCM-equipped PV systems can achieve higher energy yields and better performance, demonstrating the innovative solutions available for optimizing solar technology in humid climates. Relative humidity has been found to increase the thermal conductivity in paraffin wax, which is considered vital as it enables temperature fluctuations to be managed more efficiently, preventing excessively high temperatures from being reached by the solar cells, which can degrade their performance. Consequently, even in conditions of high relative humidity, lower operating temperatures for the solar cells can be maintained by the PCM, leading to improved energy output. It is evident from this that the inclusion of PCM has successfully controlled the PV modules' thermal state, increasing the system's overall efficiency by 2.5% and decreasing the overall temperature by 26.1%. The performance of the PV system has significantly improved according to this study, and more research on the economic advantages of integrating PCM with PV may be conducted. It is seen that the incorporation of PCM is beneficial for humid climates like Guwahati and will help researchers design such setups for similar climatic regions, as no such study has been carried out earlier and studies for non humid climtaes show lesser improvements. Moreover, future studies can be done on the encapsulation of paraffin wax or the addition of nanoparticles and using them for pasiive cooling of PV.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Pallavi Roy	✓	✓		✓	✓	✓	✓	✓	✓		✓		✓	
Bani Kanta Talukdar		✓						✓		✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author [Pallavi Roy] on request.

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