SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V12I10P106

Volume 12 Issue 10, 69-78, October 2025

Original Article

Phase Change Material Application in Photovoltaic Systems: Performance Analysis and Optimization

Pallavi Roy[1], Bipul Kumar Talukdar[2], Bani Kanta Talukdar[3], Snigdha Borah[4]

[1,4]*Girijananda Chowdhury University, Guwahati, Assam, India.*
[2]*Jorhat Engineering College, Jorhat, Assam, India.*
[3]*Assam Engineering College, Jalukbari, Assam, India.*

[1]*Corresponding Author : pallavi_ee@gcuniversity.ac.in*

Received: 04 August 2025 Revised: 06 September 2025 Accepted: 05 October 2025 Published: 30 October 2025

Abstract *- Phase Change Material (PCM) can play a significant role in optimizing Photovoltaic (PV) systems' Performance, thereby providing a workable solution for improved solar energy conversion and effective thermal management. This paper discusses the effect of various PCMs, i.e., Beeswax, paraffin wax, soy wax, and paraffin wax mixture, on the PV panel performance for different PCM thicknesses and tilt angles under varying solar intensities. Experimental results show that both solar concentration and PCM thickness are influential factors for the efficiency and power generation of the PV panels. Among the tested materials, Beeswax consistently demonstrated superior Performance, maintaining higher efficiency across all solar intensities. Thicker PCM layers were found to improve thermal control, reducing panel temperature and thereby increasing efficiency, particularly under high solar irradiance. Notably, the Beeswax–paraffin blend showed moderate efficiency gains at a 45° tilt, while Beeswax alone achieved the highest efficiency improvement of 29.87% under increased thickness and sun intensity. These findings provide important insights into the role of PCMs in thermal management of PV systems and support the potential of Beeswax as a feasible option for enhancing solar energy conversion in real-world applications.*

Keywords *- Phase Change Materials, Photovoltaic systems, Temperature management, Solar concentration, Thermal management, Performance enhancement.*

1. Introduction

With the global shift toward sustainable energy, Photovoltaic (PV) technology has emerged as a vital contributor to renewable electricity generation [1]. However, a significant limitation of PV systems is their sensitivity to temperature. As the temperature of PV panels is increased by radiation from the sun, their efficiency decreases with the increase in the temperature of the cells, which adversely affects the electric power production [2]. Therefore, Good thermal management is important to keep the PV working optimally, especially if working in one of those places with sufficient solar concentration [3].

The Phase Change Materials (PCMs) have received great attention as a means of passive thermal management for PV system applications [4]. During the transformation from liquid to solid (on/during and after solar irradiation), PCM can absorb and store excessive heat, and whilst the temperature decreases, PCMs can release heat, keeping the nominal operating temperature of the PV module (liquid to solid). The effectiveness of PCMs depends on several factors, including their thermal properties, melting points, encapsulation methods, and integration techniques [5].

Several studies have demonstrated the potential of PCMs in improving PV performance through thermal control. For instance, Nabwey et al. reported a 92% efficiency gain using sand core pellets encapsulated in paraffin, highlighting the enhancement of heat absorption from 7 to 48 kJ/min [6]. Similarly, Arifin et al found that Beeswax decreased the PV panel temperature from 60.7°C to 52.5°C, which increases the PV panel efficiency by 0.94% under 1100 W/m2 irradiance [7]. Organic PCMs, like paraffin and Beeswax, are generally preferred for thermal dependability, supported by Verma et al. [8], who encapsulated fins under PV-PCM systems to enhance heat transfer and prolong the panel life.

The integration of PCMs is not limited to conventional PV systems. Hybrid PV/T-PCM systems, which generate both thermal and electrical energy, have shown promising results. Rosli et al. reported an efficiency improvement up to 91.17% by optimizing mass flow rates and solar irradiance in PV/T systems with PCMs [9]. Al-Yasiri et al. further demonstrated that incorporating PCMs into building envelopes can improve energy efficiency by up to 44.16%, particularly in cold climates [10]. Sharma et al. demonstrated that the integration of a PCM in BIPV systems resulted in an increase of 7.7% in electrical efficiency and a decrease in module temperature by 3.8°C [11]. Additionally, Sarwar et al. investigated a Concentrated PV-PCM setup using S-series salt-based PCM, which attained 54.4% net efficiency, outperforming conventional crystalline PV panels [12]. Ma et al. discussed the investigations of PV-PCM and PV-ST-PCM systems for enhancing thermal control and efficiency, emphasizing research issues and expressing future challenges [13]. Klugmann et al. investigated PCM use for thermal management in PV systems, comparing Performance and current-voltage characteristics with and without PCM layers [14]. Jabar et al. explored PVT-PCM hybrid technology for dual electricity and thermal energy generation, identifying it as a promising clean energy solution despite market adoption challenges [15].

The optimization of the system parameters is useful for increasing the efficiency of PCM-based PV systems. Liu et al. emphasized the significance of mass flow rate and cooling pipe diameter on the opportunity for energy recovery with a hybrid VTW-PV/T-PCM system, with an annual output of 20,700 kWh [16]. Khanna et al. used simulation tools to determine optimal PCM container depths between 2.4 cm and 5.3 cm, depending on solar radiation and wind azimuth [17]. Lv et al proposed their PVTEG-PCM hybrid system and found that 30 mm of PCM with a melting point of 42°C could reduce PV temperature effectively [18]. Prieto et al. advanced the thermal conductivity of PCMs by adding metal wool to resin to increase thermal Performance for the industrial scale of thermal storage [19]. Durez et al. evaluated PV panels with RT21, RT35, and RT44 PCMs using a MATLAB-optimized model, achieving up to 39% temperature reduction and a 6% efficiency gain, with RT21 performing best [20].

Several studies have also adopted modeling and simulation approaches to evaluate system performance under varied conditions. Wu et al. reviewed PCM integration strategies, emphasizing their benefits in passive energy-saving building applications [21]. Firoozzadeh et al. [22] and Yu et al. [23] discussed material selection and integration challenges, providing a roadmap for future innovations in PV-PCM systems. Lizcano et al. documented energy yield increases and temperature drops of up to 15°C in PV modules tested in Delft and Catania [24]. Meanwhile, Naghdbishi et al. analyzed the effects of environmental temperature and PCM volume fraction using numerical simulations [25].

The results from the field testing performed by Singh et al. [26] and under hot climate conditions, Maghrabie et al. [27] affirmed the concept of using PCMs as a viable means for enhancing the Performance of the PV module and making it commercially feasible by reducing the temperatures of the clipping module with the consequent increase in the PV outputs. While things have gotten better, there are still problems. One of the most vital issues is the long-term. PCM reliability, especially leakage, degradation, and thermal instability, over multiple cycles. This encapsulation practice is still under-represented, especially when tailored for specific use in a vast range of environmental conditions. Research by Khanna et al. [17] and Sharma et al. [11] proved that apart from the need for geometric parameters of the environment, there is a critical need to have dynamic energy management systems for thermal comfort optimization. The above observations are recently continued by reviewed works of Sharaf et al. [5], Huang et al. [28], and Wu et al. [21], for illustrating the potential of PCBs incorporation in building and PV applications, and ending up with recommendations on Standardization, Affordability, and Climate-based Design. An additional point to be considered for the Photovoltaic PCM Integrated System is implementing a smart duty energy management system for thermal control components and standardization of the test payload to achieve the performance assessment.

In many studies, paraffin wax has successfully been added to PV modules to lower panel temperatures and improve PV efficiency. For example, the effects of the paraffin-based PCM in cooling panels have been demonstrated by Hasan et al. to be capable of cooling the panels by up to 5°C, corresponding to a power output increase of 3-4% [29]. As for the former, Elarga et al. found that Beeswax's thermal conductivity is somewhat lower and its adaptability to the environment is higher than that of the latter [30]. More recently, soy wax has become popular as a renewable PCM, and its application in PV cooling in moderate climates has been reported by Hoseinzadeh et al. [31].

The combination of different PCMs, e.g., a PCM composed of Beeswax and paraffin, is an emerging strategy to optimize the thermal properties of single PCMs. This study is an approach that incorporates the high latent heat of paraffin, thermal buffering, and the natural origin of the Beeswax. These concentrates' thermal and long-term stability is unknown; therefore, comparative studies are needed.

Apart from the right choice of PCM, other system design parameters like PCM thickness, PV tilt angle, and solar intensity are some of the significant factors affecting the Performance. The heat absorption ability is highly related to the diameter of the PCM layer; therefore, the thinner PCM layer will be capable of reaching saturation in a short period, while the increased thermal storage of the thicker PCM layer will be accompanied by an increase in heat transfer resistance. Studies by Khanna et al. [17] and Agyenim et al. [32] state that the optimum value for the thickness of PCM is encountered for the balance between thermal Performance and material consumption.

Similarly, Moharram et al. [33] report that tilt angle standardization improves irradiance and affects PCM performance by modifying thermal flux pathways. Furthermore, variations in solar intensity throughout the day and across seasons influence both the rate of heat gain and the frequency of PCM phase transitions, highlighting the need for adaptive design strategies to ensure effective PCM application. While various organic and inorganic PCMs have demonstrated effectiveness across different configurations, significant research gaps related to their performance optimization, economic feasibility, and durability assessment remain largely evident in the existing literature.

The synergistic effects of varying PCM thickness, panel orientation, and environmental factors are still underexplored, particularly regarding PCM blends. The present paper presents an empirical analysis that contributes to the developing body of research by systematically examining the performance impacts of Beeswax, paraffin wax, soy wax, and Beeswax–paraffin wax blends under varying PCM thicknesses, tilt angles, and solar intensities. The results are expected to reveal some important aspects for the optimal material choice and design for the support of real-world applications and for a large-scale application of PCM-enhanced PV systems. The novel contributions of the present research include:

(a) Experimental observations on the optimal thickness of various PCMs integrated with PV panels, while ensuring structural integrity and economic feasibility.
(b) Detailed comparative investigation of multiple PCMs, namely, Beeswax, paraffin wax, soy wax, and their blends, highlighting their relative effectiveness in improving PV panel performance
(c) Inspection of degradation mechanisms in paraffin wax, soy wax, and Beeswax, alongside regional adaptability, and a detailed economic and long-term durability analysis for scalable implementation.

The structure of this article is outlined as follows: Section 2 provides the experimental setup for the study. Section 3 then gives in detail the results of the experiments along with the corresponding analysis. Finally, Section 4 concludes the article and underscores prospective avenues for further research in the domain.

2. Experimental Setup

Figures 1 and 2 present the experimental setup for the present study. PCMs of various thicknesses are tested inside a building with a 500W halogen lamp as an artificial sun, and the Performance is investigated for a PV panel. For this purpose, PCMs with different thicknesses are experimented with a 500W halogen light as an artificial sun in the test room, and the Performance of the PV panel is investigated. Two PV panel types are used: one is combined with pure PCM, while the other is used as a reference. The PV panels' short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}) are measured with a multimeter instrument for electrical output and efficiency. Additionally, the distribution of temperature on the reference and PV-PCM panels' front and rear surfaces is tracked via an infrared thermometer. I_{SC}, $V_{OC,}$ and front as well as rear surface temperatures are recorded at 15-minute intervals throughout each experiment on both the PV panels. Both panels are angled 45 degrees at the start of the test. Any dust buildup is cleaned with dry cotton. To ensure accuracy, the two 50-watt PV panels are calibrated prior to testing. A variety of PCM formulations, such as Beeswax, paraffin wax, soybean wax, and a 2:1 combination of beeswax and paraffin wax, are added to the experimental panel, whereas the reference panel is left without PCM. The PV panel is kept behind different thicknesses of layers (0.5cm, 1cm, 1.5cm, and 2cm) to analyze the role of PCM thickness. Table 1 gives the data applied in the experimental setup.

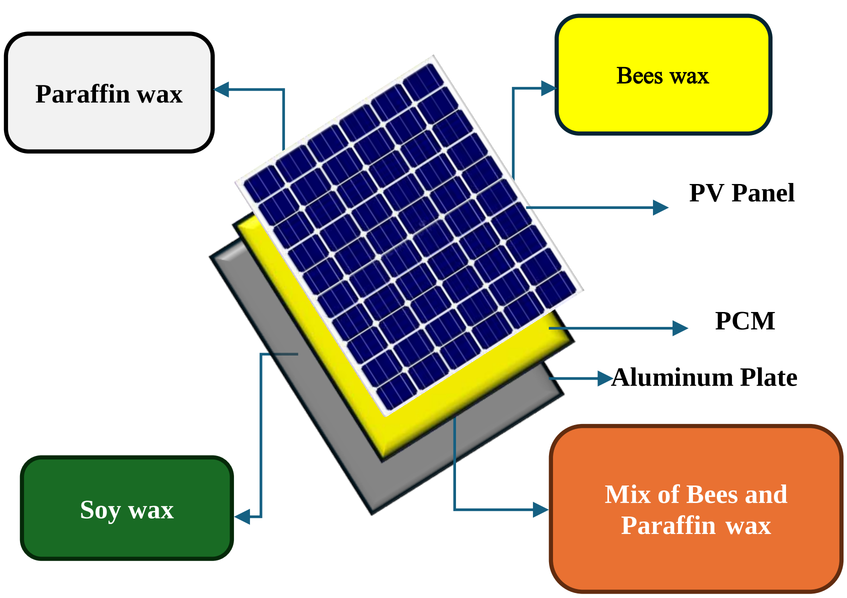

Fig. 1 Experimental setup: Coating of paraffin wax, soybean wax, beeswax, and a mixture of beeswax and paraffin wax on a PV panel

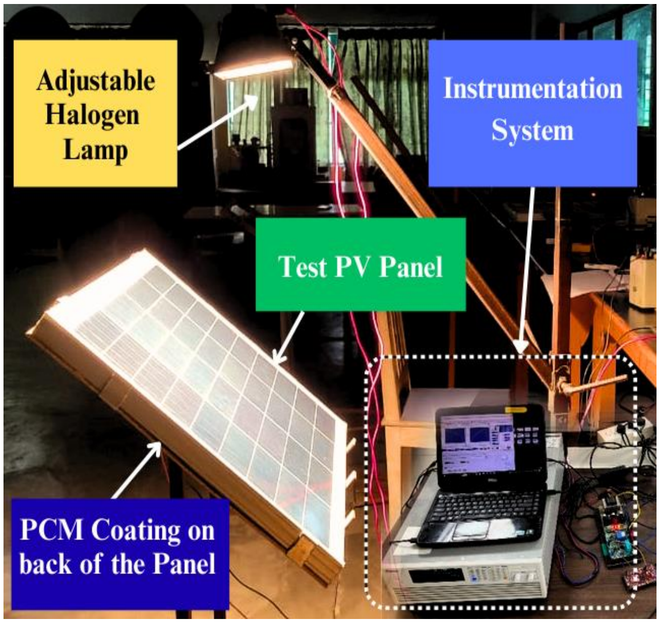

Fig. 2 Experimental setup: PV panel with adjustable Halogen lamp

Table 1. Data considered in the experimental setup [34]

Radiation (W/m^2) (Halogen lamp)	Distance between PV panel and Lamp (cm)
200	119.38
413	95.00
620	82.50
821	67.30
1016	50.00

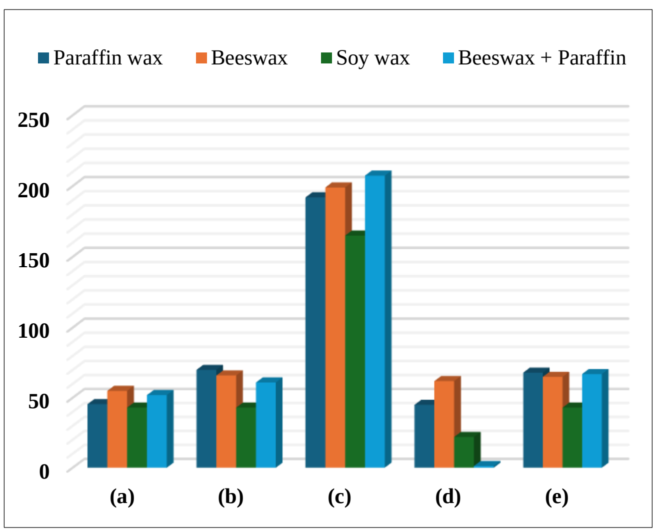

Fig. 3 Thermal properties of different wax types (a) Lowest temperature at melting (◦C), (b) Peak temperature at melting (◦C), (c) Enthalpy of melting (J/g), (d) Lower limit for complete melting (◦C), and (e) Upper limit for complete melting (◦C)

As for the PCM line of the present work, the thermal properties are presented in Figure 3. The DSC heat rate for all the PCMs is taken as 5°C/min. It is observed that Beeswax has the highest melting enthalpy and the widest melting range, making it suitable for heat storage and superior thermal management. Paraffin wax has a moderate enthalpy, which can absorb heat quickly but has less stability. Soy wax has the lowest enthalpy, followed by the beeswax and paraffin blend, and a narrow melting range, limiting its cooling potential at higher irradiance. The Beeswax–paraffin blend presents intermediate characteristics, amalgamating the latent heat capacity of Beeswax with the quicker response of paraffin. These thermal properties affect their Performance in thermal management of PV as discussed in the later sections.

3. Results and Discussion

3.1. Electrical Performance of the PV System

To find the optimal thickness for the tilt angles in the definition, the average value of the power produced is considered in the case of five different solar concentrations for thicknesses of 0.5 cm, 1 cm, 1.5 cm, and 2 cm. The thickness that resulted in the highest average power output is designated as the optimal thickness. This identified optimal thickness is subsequently applied across different tilt angles to evaluate Performance. The maximum power output (P_{max}) of PV panels at varying tilt angles and solar concentrations is detailed in Figures 4 to 7. The analysis of the tests shows that the PCM level thickness is one of the most important reasons for obtaining the optimal output for all PCMs when the sunlight exposure level is varied, providing an efficient thermal control.

The use of Beeswax as the PCM for the PV panel exhibits better Performance with a higher solar concentration, as shown in Figure 4. The test indicates a maximum power output (P_{max}) of 43.84W at 1016 W/m² with a 0.5 cm layer, and of 49.25W with a 2cm layer under the same solar concentration. Additionally, Figure 4 illustrates that a thicker layer of Beeswax yields higher outputs under partial shading conditions.

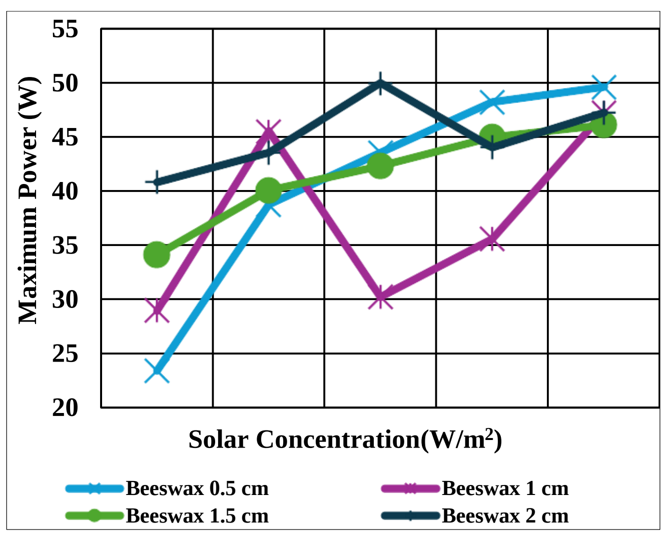

Fig. 4 PV output with increased solar concentration at varying thickness of beeswax layers

The PV panel using paraffin wax as a PCM shows increased power output and efficiency with rising solar concentration. Figure 5 indicates a maximum power output of 14.33W at 0.5cm thickness and 200 W/m², while the maximum power output reaches 49.62W at 2 cm thickness and 1016 W/m², demonstrating better thermal management with thicker layers.

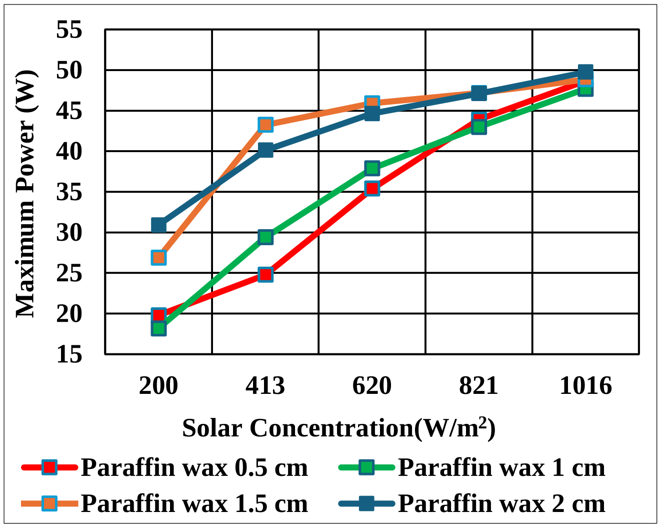

Fig. 5 PV output with increased solar concentration at varying thickness of paraffin wax layers

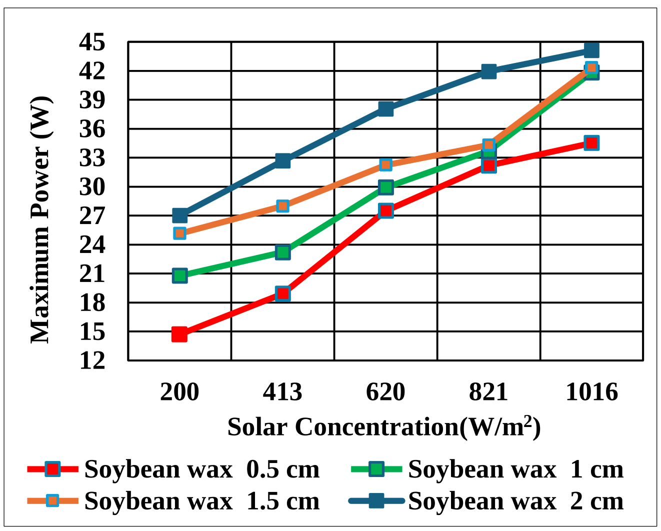

Fig. 6 PV output with increased solar concentration at varying thickness of soybean wax layers

In Figure 6, the PV panel using soybean wax as a PCM shows variations in power output with thickness and solar concentration. It indicates a minimum power output of 14.69W at 0.5 cm thickness and 200 W/m², while the maximum power output reaches 44.1W at 2 cm thickness and 1016 W/m², highlighting improved thermal management with thicker layers. Figure 7 demonstrates the Performance of the Paraffin wax and Beeswax mixture as a PCM in PV panels at different thicknesses and solar concentrations. The maximum power output is 14.33 W at 0.5 cm thickness and 200 W/m², while the P_{max} reaches 46.59W with a 2cm thicker layer of the mixture at 1016W/m² solar concentration. In all the cases, thicker layers exhibit better output power because greater material volume enhances heat storage capabilities, leading to better power output. However, a thicker layer beyond 2 cm is not preferred as this could make the system bulky and could provide thermal resistance in the system.

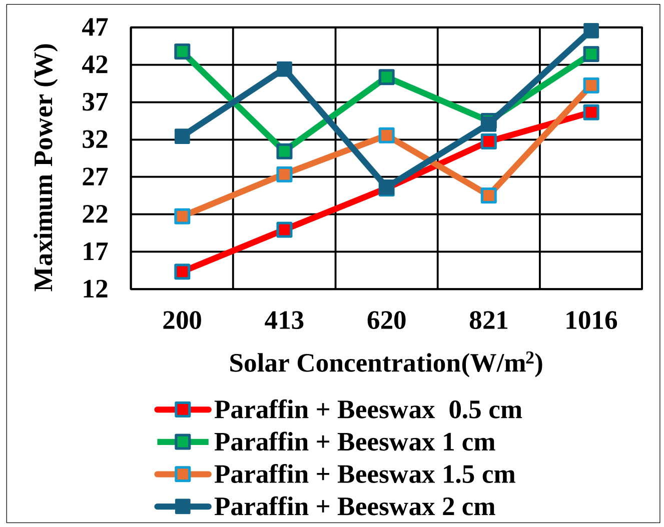

Fig. 7 PV output with increased solar concentration at varying thickness of a mixture of paraffin and beeswax layers

Comparing the panel efficiencies of different PCMs with a given tilt angle retrieved from the available PV panels in Table 2, with a thickness of 2 cm. It was observed that the incorporation of PCM improves PV efficiency at higher solar intensities. The highest efficiency is achieved at a tilt angle of 45° and a solar concentration of 1016 W/m².

Among the materials tested, beeswax and paraffin wax demonstrated superior thermal regulation at elevated solar concentrations, achieving maximum efficiencies of 29.87% and 28.34%, respectively, at 1016 W/m² and a 45° tilt. While the systems show satisfactory efficiency levels, these improved fuels, soy wax, and beeswax-paraffin wax blends still have some improvements for analysis. However, at lower intensities and certain non-optimal tilt angles, the non-PCM panel performs better than all the PCM-integrated panels. This is due to the fact that at lower intensities, the mass of the PCM delays heat absorption and may introduce thermal resistance, which results in reduced energy conversion. Thus, the application of PCM is effective primarily at higher solar intensities, where there is a greater need for heat absorption and thermal regulation. These findings indicate that Beeswax is slightly more efficient than paraffin wax and offers excellent sustainability and thermal stability, making it a preferable choice for long-term PCM-PV integration in suitable climates.

Table 2. PV Panel efficiency at varying tilt angles and solar concentrations

Tilt Angle	Solar Concentration (W/m²)	Efficiency (%) at 2cm thickness				
		Without PCM	Paraffin wax	Beeswax	Soybean wax	Mixture of Paraffin and Beeswax
15°	200	08.73	06.06	06.44	10.11	07.79
	413	09.61	05.87	06.32	09.83	07.51
	620	10.56	06.13	06.78	13.10	07.63
	821	11.50	07.57	15.91	18.33	07.96
	1016	18.32	08.72	08.53	20.94	10.99
30°	200	09.36	07.16	08.98	10.30	10.06
	413	10.32	06.78	09.86	13.02	11.15
	620	10.76	06.78	10.72	15.72	13.64
	821	11.68	08.58	11.73	17.02	16.06
	1016	20.47	12.52	18.72	24.63	20.35
45°	200	10.48	12.31	13.29	11.78	11.88
	413	08.11	14.87	15.56	13.86	13.43
	620	14.25	18.52	19.54	16.65	15.72
	821	17.97	26.33	26.36	21.46	20.76
	1016	21.82	28.34	29.87	26.78	24.37
60°	200	09.10	09.03	10.15	08.42	09.61
	413	09.96	09.96	09.44	09.61	10.14
	620	11.48	11.46	11.45	11.71	11.87
	821	14.55	15.46	14.61	15.84	16.00
	1016	20.60	22.76	20.81	22.45	19.36

Table 3. Comparative analysis of paraffin wax, soy wax, and beeswax as PCMs in large-scale PV systems

Factor	Paraffin Wax	Soy Wax	Beeswax	Impact on Large-Scale PCM PV Systems
Material Cost (₹/kg)	₹170-₹420	₹250-₹580	₹670-₹1250	Paraffin is the most cost-effective PCM
Encapsulation Cost (₹/kg)	₹830-₹2,500(Micro) /₹1,250-₹3,330 (Micro)	Similar to paraffin	Higher due to viscosity	Encapsulation is necessary, but it increases cost by 30%-60%
Installation Cost (₹/kW)	₹12,500-₹33,000	Slightly higher	Highest due to material cost	Adds to upfront investment but improves Performance
Annual Maintenance Cost (₹/kW)	₹830-₹2,100	Similar to paraffin	Moderate	PCM systems require low maintenance
Efficiency Improvement	+5%-20%	+5%-15%	+10%-25%	Increases energy output and ROI
Annual Energy Output(kWh/kW)	1,650-1,800	1,600-1,750	1,700-1,850	More output compared to non-PCM PV
ROI Period	6-8 years	7-9 years	8-10 years	The payback period is shorter in high-radiation areas.
Major Challenges	Leakage, Phase separation	Oxidation, polymerization	Brittleness, oxidation	Long-term degradation affects sustainability
Cost Reduction Strategies	Composite PCMs, bulk production	Stabilizers, antioxidants	Smart encapsulation	Innovation in material science can lower costs.

Table 4. Comparison of degradation mechanisms in paraffin wax, soy wax, and beeswax

Degradation Mechanism	Paraffin Wax	Soy Wax	Beeswax
Thermal Cycling	- Volume expansion and contraction cause cracking and leakage over time. - Reduces thermal conductivity and stability.	- Molecular structure hardens or softens, reducing latent heat capacity. - More susceptible to degradation than paraffin wax.	- Decomposes at high temperatures, leading to brittleness. - Loses heat storage capacity over multiple cycles.
Chemical Breakdown	- Oxidation forms by-products, lowering thermal stability. - Evaporation of light hydrocarbons reduces long-term effectiveness.	- Contains unsaturated fatty acids, which oxidize and polymerize, leading to rancid odors. - Structural breakdown affects heat absorption properties.	- Natural esters and fatty acids undergo oxidation, causing discoloration and material degradation. - Forms residues that reduce thermal Performance.
Phase Separation	- Hydrocarbon components segregate over time, leading to uneven melting behavior. - Results in inconsistent heat absorption and dissipation.	- Fatty acid components separate upon melting, causing waxy deposits. - Leads to reduced efficiency in heat transfer.	- Organic compounds separate at high temperatures, increasing viscosity. - Alters the melting and solidification properties, affecting efficiency.
Durability	Moderate – Can last long but is prone to phase separation and oxidation.	Lower – More vulnerable to oxidation and polymerization than paraffin wax.	Higher – More resistant to leakage but still degrades under prolonged thermal stress.
Mitigation Strategies	Encapsulation, thermal stabilizers (e.g., nanoparticles), and composite PCMs.	Blending with stabilizers, encapsulation, and antioxidant additives.	Encapsulation, adding natural stabilizers, and optimizing heat cycles.

Table 5. PCM performance in different climatic conditions

Climatic Condition	Key Characteristics	PCM Performance	Challenges	Optimal PCM Selection
Hot Climates	High daytime temperatures, cooler nights	Efficient at absorbing heat during the day and releasing it at night. Reduces cooling needs.	If PCM's melting point is too low, it may not fully solidify. High humidity can degrade Performance.	PCMs with higher melting points (e.g., 40-60°C).
Cold Climates	Low temperatures, long winters	Limited energy absorption if the ambient temperature remains too low for phase change.	PCM may freeze and become ineffective if temperatures dip too low.	PCMs with lower melting points (e.g., 15-30°C).
Temperate Climates	Moderate seasonal temperature fluctuations	Good balance for regulating indoor temperatures year-round. Reduces heating/cooling needs.	PCM must align with average daily temperatures.	PCMs with moderate melting points that match daily temperature variations (e.g., 20-25°C).
High Humidity	Moist, damp environments	High humidity can degrade PCM by affecting phase transitions and causing moisture absorption.	Potential for degradation and altered phase change behavior.	Moisture-resistant encapsulated PCMs.
Desert or Extreme Dry Conditions	Intense daily temperature fluctuations, low humidity	It is highly effective due to large temperature swings; it absorbs heat during the day and releases it at night.	PCM must handle extreme temperature variations without exceeding thermal stability.	PCMs with higher melting points (e.g., 40-60°C).
Tropical Climates	High, consistent temperatures, limited diurnal variation	Limited Performance for passive temperature regulation due to small temperature fluctuations.	Lack of temperature variation may prevent significant phase change.	PCMs with melting points slightly above ambient temperatures (e.g., 30-35°C).

Table 6. Comparison of the present study with existing studies

Source	Type of PCM used	Methodology	Key Findings
Present study	Beeswax, Paraffin, Soy, Beeswax–Paraffin blend	A 500 W halogen lamp was used in an indoor controlled environment for different radiation levels, various tilt angles, and PCM thicknesses varied from 0.5 to 2 cm.	The efficiency increased upto 29.87% for Beeswax, at 2 cm, 1016 W/m², 45° tilt) and a Pmax of 49.25 W, a much better improvement than other outdoor works reported
[17]	Paraffin-based PCM	Numerical modeling of PV–PCM module	Increased efficiency upto 7-12 % for optimum thickness of 2.4–5.3 cm
[20]	RT21, RT35, RT44 PCMs	MATLAB-based optimization model	Efficiency increased to 6% with RT21 and a 39% reduction in module temperature.
[24]	Paraffin + nano-additives	Outdoor field test (Delft, Catania)	The daily yield increased by 3 to 6%, and a temperature reduction of 15°C
[26]	Paraffin wax with containers	Outdoor field test under a hot climate	Efficiency improvement upto 5 to 8 % but major convective heat losses

3.2. Economic Feasibility and Long-Term Durability Analysis of PCM in PV Application

Table 3 presents a comparative economic analysis of the PCMs under consideration. With material prices ranging from ₹170 to ₹420 per kg, paraffin wax is the most economical PCM. However, to prevent leaks, it needs to be encapsulated (₹830 to ₹2,500 per kg for micro, ₹1,250 to ₹3,330 per unit for macro). Low yearly maintenance expenses (₹830–₹2,100 per kW) are associated with installation expenditures that range from ₹12,500 to ₹33,000 per kW. By raising yearly energy output to 1,650–1,800 kWh per kW, PCM integration lowers the ROI period to 6–8 years and increases PV efficiency by 5%–20%. Although beeswax and soy wax have a higher thermal stability, they are more costly (between ₹250 and ₹1,250 per kg) and break down more quickly if not properly stabilized. Phase separation, material deterioration, and high encapsulation costs are major obstacles; nevertheless, there are advancements in composite PCMs, large-scale manufacturing, and intelligent encapsulation. Phase separation, material deterioration, and high encapsulation costs are major obstacles; however, large-scale production can increase cost-effectiveness. Smart encapsulation and composite PCM advances. In areas with high temperatures, where efficiency improvements optimize financial returns, PCM-based cooling is most practical.

Table 4 presents the durability investigation for the various waxes. The application of a layer of PCM is found to enhance the duration and overall efficiency of PV systems [35]. The table shows that Beeswax, soy wax, and paraffin wax have different breakdown rates for photovoltaic applications. Soy wax is prone to oxidation and polymerization, which diminishes its efficiency. In contrast, paraffin wax undergoes phase separation, oxidation, and leakage. While Beeswax is more stable, it eventually becomes brittle and discoloured over time. Paraffin wax is the most economical PCM available, and encapsulating it can improve its Performance. Research has shown that even after aging, paraffin wax exhibits better efficiency. However, Beeswax would be a suitable and sustainable replacement for paraffin wax for low-temperature thermal energy storage applications, such as PV systems [36, 37]. Additionally, incorporating various materials into Beeswax, such as nano Fe_2O_3 particles or graphite powder, can enhance. It has thermal storage properties, even at higher temperatures [38].

Separately, it has been reported that the application of PCM strongly reduces the temperatures of PV panels and enhances the efficiencies of PV systems, mainly in hot climatic conditions [20]. The efficiency of the PV and PCM hybrid technologies depends on the climatic conditions. Thus, the climate of the place is very important to take into consideration while putting PCM in PV systems [4]. Table 5 provides an abridged view of the variation in PCM performance among varying climate regimes and additional challenges and necessary PCM selection criteria within that climate.

3.3. Comparation with Existing Research Findings

A comparative analysis of the results of the present study is done with other existing research to evaluate the contribution of this study. It is observed that the present study yields a better efficiency level than the reported studies and covers a wide range of PCMs and variations of various parameters like tilt angles, radiation level, and PCM thickness. The enhancement in the efficiency level can be ascribed to the controlled indoor environment and optimization of multiple parameters.

4. Conclusion

This paper confirms the fact that PCM type, PCM thickness, and solar intensity are significant for Pmax and PV panel system performance and efficiency. For the Beeswax, the minimum Pmax is 14.33 W at the thickness of 0.5 cm, 200 W/m2, and the maximum Pmax of 49.25 W at the thickness of 2 cm, 1016 W/m2, while 13.29% to 29.17% efficiency at 45 °.The Pmax of paraffin wax is 47.68 W at a thickness of 1 cm and a heat flux of 200 W/m2, and the Pmax of paraffin wax is 49.62 W at a thickness of 2 cm and a heat flux of 1016 W/m^2, and the efficiency increases from 12.31% to 28.34%.

For soy wax, the maximum Pmax is 14.69 W at 0.5 cm thickness and 200 W/m2, and the maximum Pmax is 44.1 W at 2 cm thickness, 45o tilt and 1016 W/m2, and the efficiency is 11.78%-26.78%. For the beeswax-paraffin wax composite, the efficiency of the composite is increased from 11.88% at 2 cm thickness and 200 W/m2 to 24.37% at 45 degrees tilt and 1016 W/m2. The results show that the thermal regulation is improved as the PCM layer becomes thicker, overheating is reduced, and the PV performance is improved with increasing solar concentration.

Among the materials tested, a 2cm thick beeswax and a 2cm thick paraffin wax produce the highest power outputs and highest efficiencies. Thus, it can be said that this research work has demonstrated the efficient integration of PV with PCM and can be considered a typical candidate for improving the energy and thermal management efficiency of many laboratory units in the future. Thermal stability, encapsulation integrity, mechanical stress resistance, and environmental conditions are all important factors to consider when determining the longevity of PCMs in PV applications. Phase transitions of PCM over time can degrade PCM materials, decreasing effectiveness and capacity for thermal storage.

Other factors affecting longevity are leakage or structural failure, and material incompatibility with PV panels. Climatic environments such as high humidity and high temperature will influence PCM performance and require different formulation adaptation to multi-ambient environments. The advantages gained from the temperature management, the better encapsulation, and more efficient composites, together with the periodic maintenance, are shown to be indispensable for the economic viability and the long-lasting maintenance of this design. In addition, to encourage the use of PCMs in practice, the formulation of PCMs, PCM encapsulation, and integration into intelligent energy management systems are required to be more stable and efficient, for homogenous functioning, which can be the subject of future development.

References

[1] Prabhakar Sharma, and Ritesh Kumar Mishra, "Comprehensive Study on Photovoltaic Cell's Generation and Factors Affecting its Performance: A Review," *Materials for Renewable and Sustainable Energy*, vol. 14, no. 21, pp. 1-28, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[2] Levon Ghabuzyan et al., "Thermal Effects on Photovoltaic Array Performance: Experimentation, Modeling, and Simulation," *Applied Sciences*, vol. 11, no. 4, pp. 1-15, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[3] Razan El Kassar et al., "Phase Change Materials for Enhanced Photovoltaic Panels Performance: A Comprehensive Review and Critical Analysis," *Energy and Built Environment*, vol. 6, no. 4, pp. 655-675, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Liang Tang et al., "Thermal-Management Performance of Phase-Change Material on PV Modules in Different Climate Zones," *Energies*, vol. 17, no. 23, pp. 1-18, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Mohamed Sharaf, Mohamed S. Yousef, and Ahmed S. Huzayyin, "Review of Cooling Techniques Used to Enhance the Efficiency of Photovoltaic Power Systems," *Environmental Science and Pollution Research*, vol. 29, no. 18, pp. 26131-26159, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Hossam A. Nabwey, and Maha A. Tony, "Enhancing the Performance of Paraffin's Phase Change Material through a Hybrid Scheme Utilizing Sand Core Matrix," *Scientific Reports*, vol. 14, no. 1, pp. 1-13, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[7] Zainal Arifin et al., "Photovoltaic Performance Improvement with Phase Change Material Cooling Treatment," *International Journal of Heat and Technology*, vol. 40, no. 4, pp. 953-960, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[8] Kamesh Verma et al., "Photovoltaic Panel Integration Using Phase Change Material (PCM): Review," *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, vol. 10, no. 1, pp.444-453, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[9] Mohd Afzanizam Mohd Rosli et al., "Performance Optimization of a Simulation Study on Phase Change Material for Photovoltaic Thermal," *CFD Letters*, vol.14, no. 9, pp. 32-51, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[10] Qudama M. Q. Al-Yasiri, and Márta Szabó, "Performance Assessment of Phase Change Materials Integrated with Building Envelope for Heating Application in Cold Locations," *European Journal of Energy Research*, vol. 1, no. 1, pp. 7-14, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[11] Shivangi Sharma et al., "Performance Enhancement of a Building-Integrated Concentrating Photovoltaic System Using Phase Change Material," *Solar Energy Materials and Solar Cells*, vol. 149, no. 29-39, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[12] Jawad Sarwar et al., "Performance Analysis and Comparison of a Concentrated Photovoltaic System with Different Phase Change Materials," *Energies*, vol. 14, no. 10, pp. 1-17, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[13] Tao Ma et al., "Using Phase Change Materials in Photovoltaic Systems for Thermal Regulation and Electrical Efficiency Improvement: A Review and Outlook," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 1273-1284, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[14] Ewa Klugmann-Radziemska et al., "The Possibility of Phase Change Materials (PCM) Usage to Increase Efficiency of the Photovoltaic Modules," *MATEC Web of Conferences*, vol. 18, pp. 1-7, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[15] Muhammad Hussin Abdul Jabar et al., “The Solar End Game: Bibliometric Analysis, Research and Development Evolution, and Patent Activity of Hybrid Photovoltaic/Thermal-Phase Change Material,” *Environmental Science and Pollution Research*, vol. 30, no. 55, pp. 116934-116951, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[16] Xiaohong Liu et al., “Optimization of a New Phase Change Material Integrated Photovoltaic/Thermal Panel with the Active Cooling Technique Using Taguchi Method,” *Energies*, vol. 12, no. 6, pp. 1-22, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[17] Sourav Khanna, K.S. Reddy, and Tapas K. Mallick, “Optimization of Solar Photovoltaic System Integrated with Phase Change Material,” *Solar Energy*, vol. 163, pp. 591-599, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[18] Song Lv et al., “Research and Numerical Analysis on Performance Optimization of Photovoltaic-Thermoelectric System Incorporated with Phase Change Materials,” *Energy*, vol. 263, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[19] Cristina Prieto et al., “Improvement of Phase Change Materials (PCM) Used for Solar Process Heat Applications,” *Molecules*, vol. 26, no. 5, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[20] Asif Durez et al., “Modelling and Optimization of Phase Change Materials (PCM)-based Passive Cooling of Solar PV Panels in Multi Climate Conditions,” *Frontiers in Energy Research*, vol. 11, pp. 1-11, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[21] Xiangxiang Wu, “Review on Phase Change Materials and Application in Building Energy Saving,” *E3S Web of Conferences: 3rd International Conference on Energy Resources and Sustainable Development (ICERSD 2020)*, vol. 236, pp. 1-5, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[22] Mohammad Firoozzadeh, Amir Hossein Shiravi, and Mojtaba Shafiee, “Different Methods of Using Phase Change Materials (PCMs) As Coolant of Photovoltaic Modules: A Review,” *Journal of Energy Management and Technology (JEMT)*, vol. 4, no. 30, pp. 30-36, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[23] Qinghua Yu, Xi Chen, and Hongxing Yang, “Research Progress on Utilization of Phase Change Materials in Photovoltaic/Thermal Systems: A Critical Review,” *Renewable and Sustainable Energy Reviews*, vol. 149, pp. 1-66, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[24] Juan Camilo Ortiz Lizcano et al., “Long-Term Experimental Testing of a Phase Change Material as Cooling Device for Photovoltaic Modules,” *Solar Energy Materials and Solar Cells*, vol. 277, pp. 1-39, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[25] Ali Naghdbishi, Mohammad Eftekhari Yazdi, and Ghasem Akbari, “Numerical Study on the Performance of a Glazed Photovoltaic Thermal System Integrated with Phase Change Material (GPVT/PCM): On the Contribution of PCM Volumetric Fraction and Environmental Temperature,” *Energy Equipment and Systems*, vol. 10, no. 2, pp. 137-168, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[26] Preeti Singh et al., “Experimental Investigation of Solar Photovoltaic Panel Integrated with Phase Change Material and Multiple Conductivity-Enhancing-Containers,” *Energy*, vol. 205, pp. 1-30, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[27] Hussein M. Maghrabie et al., “Performance Enhancement of PV Panels Using Phase Change Material (PCM): An Experimental Implementation,” *Case Studies in Thermal Engineering*, vol. 42, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[28] Jintao Huang et al., “Advances and Applications of Phase Change Materials (PCMs) and PCMs-based Technologies,” *ES Materials and Manufacturing*, vol. 13, pp. 23-39, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[29] A. Hasan et al., “Evaluation of Phase Change Materials for Thermal Regulation Enhancement of Building Integrated Photovoltaics,” *Solar Energy*, vol. 84, no. 9, pp. 1601-1612, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[30] Hagar Elarga et al., “Thermal and Electrical Performance of an Integrated PV-PCM System in Double Skin Façades: A Numerical Study,” *Solar Energy*, vol. 136, pp. 112-124, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[31] Pegah Hoseinzadeh et al., “Energy Performance of Building Integrated Photovoltaic High-Rise Building: Case Study, Tehran, Iran,” *Energy and Buildings*, vol. 235, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[32] Francis Agyenim et al., “A Review of Materials, Heat Transfer and Phase Change Problem Formulation for Latent Heat Thermal Energy Storage Systems (LHTESS),” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 2, pp. 615-628, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[33] K.A. Moharram et al., “Enhancing the Performance of Photovoltaic Panels by Water Cooling,” *Ain Shams Engineering Journal*, vol. 4, no. 4, pp. 869-877, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[34] Y.M. Irwan et al., “Indoor Test Performance of PV Panel through Water Cooling Method,” *Energy Procedia*, vol.79, pp. 604-611, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[35] Dariusz Heim et al., “Towards Improving the Durability and Overall Performance of PV-ETICS by Application of a PCM Layer,” *Applied Sciences*, vol. 11, no. 10, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[36] La Ode Mohammad Firman et al., “The Impact of Thermal Aging on the Degradation of Technical Parameter of a Dynamic Latent Thermal Storage System,” *International Journal of Thermofluids*, vol. 19, pp. 1-9, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[37] Pushpendra Kumar Singh Rathore et al., “Beeswax as a Potential Replacement of Paraffin Wax as Shape Stabilized Solar Thermal Energy Storage Material: An Experimental Study,” *Journal of Energy Storage*, vol. 68, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[38] P. Venkata Vineeth, and K. Dharma Reddy, “Experimental Investigations on Nano-Fe_2O_3/ Beeswax Phase Change Materials for Thermal Energy Storage Applications,” *Materials Today: Proceedings*, 2023. [CrossRef] [Google Scholar] [Publisher Link]