

Paraffin-Based Phase Change Materials for Thermal Management of Solar Panels

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Abstract— Solar photovoltaic (PV) modules suffer a significant decline in performance due to thermal loading during operation. Although only 15–20% of the incident solar energy is converted into electricity, nearly 80% is dissipated as heat, causing the PV cell temperature to rise beyond 65–75 °C in typical Indian conditions. This thermal accumulation results in reduced electrical efficiency, increased resistive losses, and long-term material degradation. To mitigate this challenge, the present work investigates a hybrid passive thermal management and energy-recovery system integrating Phase Change Material (PCM), Graphene-enhanced composite, and a Thermoelectric Generator (TEG). Paraffin wax was selected as the base PCM for its high latent heat capacity and chemical stability. However, due to its inherently low thermal conductivity (~0.2 W/m·K), graphene nanoplatelets were incorporated to enhance heat absorption and accelerate phase transition. A custom CNC-machined wooden enclosure was designed and fabricated with a top cut-out to hold a mini solar panel, while the interior housed the PCM composite and the TEG module. The TEG was sandwiched between the PV panel and the PCM layer to utilize the temperature difference created during both daytime and nighttime cycles.

Index Terms—PCM, TEG, Photovoltaic, Paraffin wax

I. INTRODUCTION

Solar Photovoltaic (PV) systems have become one of the fastest-growing renewable energy technologies worldwide due to their scalability, modularity, low operational cost, and ability to convert sunlight directly into electrical energy. PV modules work on the principle of the photovoltaic effect, where semiconductor materials—typically crystalline silicon—generate charge carriers upon exposure to solar radiation. These charge carriers are collected as

electrical current, enabling clean and sustainable power generation.

Although photovoltaic (PV) modules are intended to convert sunlight directly into electrical energy, a major portion of the incident radiation is converted into heat. Typically, only 15–20% of the light contributes to electricity generation, while 80–85% becomes thermal energy. This unwanted heat accumulation increases the cell temperature, decreasing efficiency and accelerating material degradation. Understanding these thermal loss mechanisms is essential for designing an effective cooling solution.

II. PROBLEM STATEMENT

The reviewed literature clearly establishes that photovoltaic (PV) modules suffer significant performance loss due to temperature rise, with studies consistently reporting an efficiency drop of 0.4–0.5% per °C. Paraffin-based Phase Change Materials (PCMs) have been widely investigated as a passive cooling solution, and researchers such as Stritih (2016) and Chandel & Agarwal (2017) have demonstrated temperature reductions of 5–12°C, resulting in improved electrical output. However, most studies highlight the major limitation of pure paraffin—it's very low thermal conductivity—which causes slow and non-uniform melting.

III. OBJECTIVES

To develop a graphene-enhanced paraffin Phase Change Material (PCM) capable of rapid and uniform heat absorption. This includes preparing a paraffin-graphene composite with improved thermal conductivity to overcome the slow melting and non-

uniform thermal response of pure paraffin, enabling more effective temperature regulation for photovoltaic (PV) modules.

IV. LITERATURE BACKGROUND

One of the most significant challenges with paraffin wax is its low thermal conductivity (~ 0.2 W/m·K). Numerous studies have attempted to overcome this. Li et al. (2022) developed an expanded graphite–paraffin composite using melt-blending and vacuum encapsulation. Their sample achieved a thermal conductivity of 7.06 W/m·K, showing how carbon-based additives drastically improve paraffin heat transfer. This work proves that adding conductive fillers makes PCM more responsive for solar applications. Huang et al. (2022) formulated a paraffin/expanded graphite/graphene/ aluminium honeycomb composite and demonstrated improved thermal regulation. Their study highlights how graphene nanoplatelets enhance heat spreading inside PCM, preventing hot spots.

Stritih (2016) conducted an experimental and numerical study showing that PCM can reduce PV temperature by up to 35.6°C, improving power output by 7.3%. This demonstrates the effectiveness of PCM in delaying thermal rise. Chandel and Agarwal (2017) performed a detailed review of PCM-based PV cooling and reported an average 5–12°C temperature reduction with efficiency gains of 4–5%. This is widely regarded as one of the strongest review papers confirming PCM's reliability. Hasan et al. (2010) studied PCMs for BIPV and achieved an 18°C reduction for 30 minutes, proving PCM's ability to buffer heat during peak irradiance. Ho et al. (2012) integrated microencapsulated PCM into PV panels and observed improved thermal stability and electrical performance.

Dimri et al. (2018) evaluated a PV–TEC hybrid system and showed that attaching a thermoelectric cooler at the PV base increases overall PV efficiency. They proved that TEG/TEC modules can interact effectively with PV heat flux. Kohan et al. (2018) simulated a hybrid PV–TEG system and reported that adding TEG increased total output power, confirming the potential of waste-heat harvesting. Rodrigo et al. (2019) analyzed passively cooled PV–TEG concentrator

modules and recorded a 2.8% efficiency improvement, showing that even small ΔT can be exploited using TEGs. He et al. (2013) studied a solar-driven thermoelectric heating/cooling system and validated that TEGs produce steady output under fluctuating solar conditions. These works establish the rationale for including a TEG in your system. Even though TEG efficiency is low, stable ΔT (achieved using PCM) boosts output.

V. PROPOSED METHODOLOGY

The workflow adopted in this project follows a systematic sequence to avoid errors at any stage. The process begins with understanding PV thermal behaviour, selecting compatible materials, and preparing the enhanced PCM composite. This is followed by the design and fabrication of a dedicated enclosure that ensures stable housing for all components. After that, the PV panel, TEG module, and PCM are integrated into a single assembly. The final stages involve installing temperature sensors, running experiments under real outdoor conditions, and recording temperature and voltage readings. The collected data is analyzed to compare baseline performance, paraffin PCM cooling, and graphene PCM cooling. This sequential workflow ensures a clear flow from design to evaluation and allows each component's behaviour to be studied in detail.

Material selection was based on thermal requirements, compatibility, safety, and practicality. A mini polycrystalline PV panel was selected due to its compact size and representative thermal characteristics. Paraffin wax was chosen as the primary PCM because of its high latent heat, suitable melting point (45– 60°C), and safe handling properties. To overcome the low thermal conductivity of paraffin, graphene nanoplatelets (1–3 wt%) were chosen as the enhancement material. A TEC1-12706 thermoelectric module was used as the TEG because it is inexpensive, widely available, and effective at converting moderate temperature differences into millivolt outputs. Plywood was chosen for the enclosure due to its light weight, insulation characteristics, good machinability, and structural rigidity. These materials collectively support efficient heat transfer, passive cooling, and experimental integration.

The preparation of graphene PCM began by melting paraffin wax using a controlled water bath at approximately 70–80°C. In this phase, the wax transitions fully into a uniform liquid without burning or thermal degradation. Once melted, a pre-measured amount of graphene nanoplatelets was introduced gradually into the molten paraffin. To ensure proper mixing, continuous stirring was performed to break any clusters and distribute the graphene evenly. After homogenization, the molten composite was poured into aluminum foil moulds or pouches and left to solidify at room temperature. The resulting graphene-enhanced PCM blocks exhibit improved thermal conductivity, enabling faster absorption of heat during PV operation.

The wooden enclosure was fabricated to house the PV-TEG-PCM assembly in a compact and thermally stable manner. CNC machining was chosen because it ensures high dimensional accuracy, clean cuts, and perfect interlocking joints. The enclosure design included a top opening for the PV panel, an internal cavity for the TEG and PCM layers, and proper routing space for sensor wiring.

VI. RESULTS AND DISCUSSION

The PV panel temperature increased rapidly under sunlight when no cooling method was applied. The panel reached a peak temperature of 45°C, which is typical for a small 5W module. When pure paraffin PCM was placed behind the panel, the maximum temperature reduced to 40°C, showing moderate cooling. The best performance was observed when graphene-enhanced PCM was used, where the panel temperature dropped further to 36°C. These temperature reductions demonstrate the effectiveness of PCM in absorbing heat during the melting phase. The addition of graphene accelerates heat conduction within the PCM, allowing it to melt more uniformly and absorb heat 46 faster. As a result, the PV module operates at a lower and more stable temperature during peak sunlight hours.

Time	Ambient (°C)	PV-temp (No PCM) °C	PV-temp (PCM) °C	PV-temp (Graphene PCM) °C
09:00	30	32	31	31
10:00	33	36	34	33
11:00	35	40	37	35
12:00	36	45	40	36
13:00	36	44	40	35
14:00	35	42	39	34
15:00	33	38	36	33
16:00	31	36	35	32

Pure paraffin PCM began melting during the late morning period. However, melting remained non-uniform, with only the outer layers liquefying initially while the inner core stayed solid for a longer duration. This behaviour is due to paraffin’s naturally low thermal conductivity. When graphene-enhanced PCM was used, melting occurred earlier and more uniformly. The improved thermal conductivity allowed heat to spread deeper and faster, leading to a more complete utilization of the PCM’s latent heat. The graphene composite also cooled faster in the evening due to improved heat dissipation, allowing the PCM to solidify fully and reset for the next cycle.

The TEG generated measurable voltage when a temperature difference developed across its surfaces. The highest observed voltage was 185 mV at a ΔT of 27°C, which was recorded during peak heating. This value was used to estimate the TEG’s performance for smaller ΔT values observed during testing.

The graphene-enhanced PCM configuration produced the most stable ΔT , leading to smoother and more consistent voltage output. Although TEG power is in the milliwatt range, it demonstrates effective waste-heat utilization in a compact form.

VII. CONCLUSION

This project successfully developed and experimentally evaluated a hybrid PV-PCM-Graphene-TEG thermal management system aimed at reducing photovoltaic panel temperature and recovering part of the waste heat as electrical energy. The system integrated a polycrystalline PV module, a thermoelectric generator (TEG), and a graphene-enhanced paraffin PCM inside a CNC-fabricated wooden enclosure. Experimental investigations

demonstrated that the PCM played a crucial role in stabilizing PV temperature during peak sunlight hours, while graphene reinforcement significantly improved heat distribution and responsiveness.

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