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Performance Improvement of Solar Photovoltaic Cells Using Phase Change Materials: A Comprehensive Review

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Abstract:

Solar photovoltaic (PV) technology is one of the most widely adopted renewable energy solutions due to its sustainability and modularity. However, the performance of PV modules is significantly affected by operating temperature, as higher cell temperatures lead to a reduction in electrical efficiency, output power, and lifespan. Phase Change Materials (PCMs) have emerged as a promising passive thermal management technique for PV systems owing to their high latent heat storage capacity and nearly isothermal behaviour during phase transition. This review paper presents a detailed and critical assessment of the use of PCMs for thermal regulation and performance enhancement of solar PV cells. The fundamentals of PV temperature effects, PCM thermophysical properties, system configurations, heat transfer mechanisms, experimental and numerical investigations, and performance improvements are comprehensively discussed. Comparative analysis with other cooling techniques, techno-economic considerations, challenges, and future research directions are also highlighted.

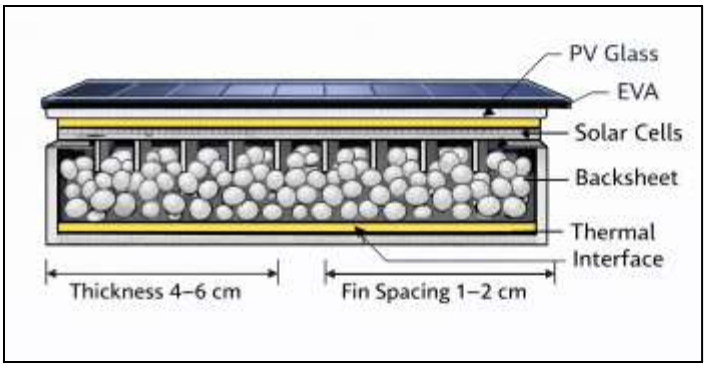
Keywords: Solar photovoltaic, phase change material, thermal management, PV efficiency enhancement, passive cooling

1.0 Introduction:

The growing demand for clean and sustainable energy has accelerated the deployment of solar photovoltaic (PV) systems worldwide. Solar PV technology directly converts solar radiation into electricity and offers advantages such as low operating cost, minimal environmental impact, and ease of installation. Despite these benefits, the electrical performance of PV modules is highly sensitive to operating temperature. Under real outdoor conditions, PV cell temperature can rise to 60–80 °C, resulting in a significant reduction in conversion efficiency. Typically, the efficiency of crystalline silicon PV modules decreases by approximately 0.4–0.5% per °C rise above the standard test condition temperature of 25 °C [1, 2]. Therefore, effective thermal management is essential to maintain optimal PV performance and extend module lifespan. Among various cooling techniques, phase change materials (PCMs) have gained considerable attention as a passive and energy-efficient solution.

PCMs absorb excess thermal energy during melting and release it during solidification, thereby maintaining the PV module temperature within a desirable range [3]. This review aims to provide a comprehensive evaluation of PV–PCM systems, focusing on performance improvement mechanisms, design configurations, experimental outcomes, and future scope.

Figure 1. Schematic of PV-PCM system design



This review focuses on: (a) types of PCMs and thermo-physical properties relevant to PV; (b) mechanical/electrical integration strategies (rear-mount, encapsulation, fins, nano-enhancements); (c) modeling approaches and governing equations; (d) reported performance improvements and metrics; (e) system-level tradeoffs, techno-economic aspects, and research gaps.

2.0 PCMs for PV: types, properties and selection criteria:

2.1 PCM families [3]

- Organic PCMs (paraffin waxes, fatty acids): good latent heat, chemical stability, low subcooling, low thermal conductivity.
- Inorganic PCMs (salt hydrates, eutectics): higher thermal conductivity and latent heat per volume, but may show supercooling, phase segregation and corrosion issues.
- Bio-based PCMs (e.g., vegetable oils, beeswax): renewable but often lower thermal stability or latent heat.
- Composite/Enhanced PCMs (NePCM): PCMs with high-conductivity additives (graphite, metal foams, nanoparticles) or encapsulated PCMs to improve cycling and conductivity.

2.2 Key selection criteria for PV applications

- Melting point (Tm): should be near the desirable operating temperature range of the PV module (commonly ~30–60 °C) so PCM operates during peak irradiation [4].
- High latent heat (L): more energy absorbed per mass/volume.
- Thermal conductivity (k): low for many organics—requires enhancement (fins, metal foam, nanoparticles) to get useful charging/discharging rates.
- Cycling stability and compatibility: minimal phase separation or chemical degradation over many cycles.
- Density, cost, flammability and environmental/safety considerations.

3.0 Integration strategies for PV-PCM systems [3]:

3.1 Rear-mounted PCM packs

PCM containers attached to the rear side of a PV module are the simplest approach. Proper thermal contact and container geometry (thin layers, channel shapes, fins) are crucial to reduce thermal resistance and achieve useful heat transfer rates. Experimental studies show that container shape and thickness strongly affect cooling performance.

3.2 Encapsulated PCM within module frame or glazing

Embedding PCM into module frames (or PV glazing/LSC frames) can provide more direct thermal coupling—useful for building-integrated PV (BIPV) and vertical installations. Numerical studies indicate careful selection of melting point and latent heat capacity is critical.

3.3 Finned and porous structures, metal foams

Adding fins or porous metal foam within PCM containers increases surface area and effective thermal conductivity, enabling faster PCM charging/discharging and better temperature control. Studies show fins and foam can substantially improve power gains over plain PCM layers.

3.4 Hybrid PV/T-PCM (thermal recovery)

PCM can be integrated with PV/T systems to store thermal energy extracted from the rear side (for water heating, space heating). Hybrid systems can achieve higher combined energy utilization and better economics under certain scenarios.

3.5 Nano-enhanced PCMs (NePCMs)

Dispersing nanoparticles (ZnO, Al_2O_3, carbon nanostructures) into PCM increases thermal conductivity and can improve charging/discharging behavior; some studies report large improvements but raise questions about long-term stability and cost.

4.0 Governing Equations [3-8]:

4.1 PV electrical performance vs. temperature

A commonly used linear model for module efficiency (or power) dependence on module temperature Tm is:

$$\eta(T_m) = \eta_{ref}\left[1 - \beta\left(T_m - T_{ref}\right)\right]$$

where η_{ref} is efficiency at reference temperature T_{ref} (usually 25°C) and β is the temperature coefficient ($\approx 0.004 - 0.005\ \text{K}^{-1}$ or -0.4 to $-0.5\% / {}^\circ\text{C}$ for many crystalline-Si modules).

4.2 Lumped energy balance for PV-PCM assembly

A lumped-capacitance representation of the PV module and PCM (single node for each) gives:

For the PV module:

$$C_{pv}\frac{dT_{pv}}{dt} = G\left(1 - \eta\left(T_{pv}\right)\right) - Q_{loss,conv} - Q_{pcm\_\text{transfer}}$$

For the PCM control volume:

$$C_{pcm}\frac{dT_{pcm}}{dt} + \dot{m}_{pcm}L\frac{df}{dt} = Q_{pcm\_\text{transfer}}$$

where:

- C_{pv}, C_{pcm} are thermal capacitances,
- G is incident irradiance (W/m^2),
- $Q_{\text{loss, conv}} = hA\left(T_{pv} - T_{amb}\right)$ (convective + radiative losses approximated),
- $Q_{\text{pem\_transfer}}$ is heat flux into PCM through interface (depends on k, contact area, fins),
- L is latent heat, f is liquid fraction; the term $\dot{m}_{\text{pcm}}\, Ldf/dt$ captures phase change energy flow.

5. Summary of reported experimental and numerical performance:

Table 1 shows a concise comparison table summarizing representative recent studies showing the range of reported results. (Values are study-specific and depend on weather, irradiance, PCM type, thickness, and enhancements.)

Table 1. Literature Survey

Study (year)	**PCM / enhancement**	**Test type**	**Typical temperature drop (°C)**	**Reported power / efficiency change**
Maghrabie et al. (2023)	Rear paraffin	Field/experimental	~7 °C reduction	~+1.2% daily average performance.
Unnikrishnan et al. (2024)	PCM with geometry optimization	Exp + simulation	~23 °C drop reported	+5.18% power in lab test.
Mazzeo et al. (2025)	Multiple PCM configs	Experimental	Up to 26 °C rear temp drop	Energy output increased up to 6.84% (best config).
Al-Salami et al. (2024)	Nano-enhanced PCM	Lab	variable	Some report large relative gains (10–20% electrical or thermal gains in controlled tests) but with caveats on scalability.

Improvements vary widely. Well-designed PCM systems typically reduce module temperature by several °C and produce modest electrical gains (1–7%) under field conditions; aggressive enhancements (nePCMs, fins + PCM + active cooling) can show higher relative gains in lab setups. System optimization, PCM melting point, thickness, conduction enhancements, and local climate timing of irradiation strongly determines benefit [6].

6. Technical tradeoffs and practical considerations

- Duration of PCM effectiveness: In long hot periods or when daytime heating exceeds PCM charging capacity, PCM can saturate (fully melted) and stop absorbing heat—reducing effectiveness during peak hours. Proper sizing and/or hybrid active cooling may be needed.
- Thermal conductivity vs. latent capacity trade-off: Adding metal fillers increases conduction but reduces volumetric latent heat density per cost and may increase weight. Optimized fin networks or metal foams often provide better trade-offs than high nanoparticle loadings.
- Cycling stability and maintenance: Salt hydrates may suffer phase segregation; organics can be flammable. Encapsulation and compatibility with module materials are essential.
- Cost and manufacturability: PCM integration increases BOM cost and complexity. Techno-economic studies suggest the payback depends on local irradiation, module cost, and whether thermal by-product is used (PV/T).

7. Recommendations for design and best practice

- Choose PCM Tm near the expected operating peak module temperature so melting occurs when cooling is most needed (often 40–55 °C for many climates).
- Enhance conduction with fins/metal foam rather than very high nanoparticle loadings when possible—for a better balance of effective charging rates and latent capacity.
- Model before prototype: perform site-specific transient simulations (hourly meteorology) to size PCM mass and thickness to avoid saturation during peak days. Lumped models are useful for first pass; enthalpy-based CFD/FEA for final design.
- Consider PV/T-PCM hybrid if thermal output can be used (water heating, process heat), this improves overall energy economics.

8. Future research directions

- Long-term cycling studies for NePCMs and composites to quantify stability, phase segregation, and performance degradation under thermal/UV/operational stress.
- Standardized field trials across climate zones to gather comparable performance and economic metrics.
- Hybrid control strategies combining PCM with passive air channels or intermittent active cooling for improved resilience.
- Life-cycle and fire-safety analysis especially for paraffin-based PCMs in rooftop and BIPV installations.
- Cost-benefit frameworks integrating module lifetime extension, performance gain, and thermal use (if PV/T). Recent reviews call for standardized reporting (Tm, PCM thickness, enhancement details, irradiance and ambient conditions)

10. Conclusions

PCMs provide a compelling passive approach to reduce PV module temperatures and recover thermal energy in hybrid systems. Under realistic outdoor conditions, PCM integration typically yields modest but useful electrical gains (commonly 1–7% in field tests; higher gains possible in optimized lab setups). The main levers for success are correct PCM melting point selection, sufficiently high effective thermal conductivity (fins, metal foam or other enhancements), proper sizing to avoid mid-day saturation, and ensuring long-term stability. For broad deployment, more standardized field comparisons and techno-economic analyses are needed.

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