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Improving heat transfer in solar cells to achieve sustainability and lower greenhouse gas emissions: A comprehensive review

Israa R. Jawad [1,*] and Mohammed Ali A. Shaban [2]

[1] *Department of Mechanical Engineering, college of engineering. Al-Nahrain University. Baghdad, Iraq.*
[2] *Department of Civil Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq.*

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Abstract

The rapid expansion of solar photovoltaics (PV) as a decarbonization technology has made module performance and sustainability central to global energy planning. Only a small portion of the incident solar spectrum is converted to electricity; the rest is dissipated as heat, which raises cell temperature, depresses voltage, and accelerates long-term degradation. Because the life-cycle greenhouse gas (GHG) intensity of PV electricity is inversely proportional to lifetime generation, improvements in thermal management can substantially lower embodied emissions per kilowatt-hour. This review integrates thermophysical principles with the latest passive and hybrid heat-transfer strategies for PV, including enhanced rear convection and heat spreading, phase-change materials (PCMs), spectrally selective radiative cooling, and hybrid photovoltaic/thermal (PV/T) and PV–thermoelectric (PV–TEG) systems. We critically examine the physics, the governing equations, and real-world performance from both laboratory and field studies. Finally, we explore how heat-transfer improvements translate into better reliability, longer lifetimes, and lower gCO_2-eq/kWh, identifying research gaps in durable coatings, recyclable PCMs, and standardized long-term field data.

Keywords: Photovoltaic Modules; Heat Transfer Enhancement; Thermal Management; Passive Cooling; Phase-Change Materials (PCM).

1. Introduction

Photovoltaic modules in outdoor conditions routinely reach 40–70 °C, well above their 25 °C rating. This increase leads to power losses of about 0.3–0.5 % per °C for crystalline silicon and somewhat lower for thin-film modules [1][2]. These temperature effects are nontrivial at scale: over a 25-year lifetime, higher operating temperatures translate into lower cumulative generation, inflating the levelized cost of electricity (LCOE) and raising life-cycle GHG emissions per kWh [3][4].

At the same time, the solar sector is expected to supply up to 30–40 % of global electricity by mid-century, much of it deployed in hot climates where thermal losses are greatest. Conventional methods—natural ventilation, tilt optimization—cannot fully offset the thermal penalty under these conditions [5][6]. This review therefore addresses the dual imperative of sustaining PV performance and minimizing environmental impact by focusing on heat transfer as a design variable.

* Corresponding author: Israa R. Jawad

2. Heat Transfer Principles in Photovoltaic Modules

2.1. Energy balance and heat fluxes

The steady-state cell temperature Tc can be expressed as

$$Qabs = Qconv + Qrad + Qcond$$

where Q_{abs} is absorbed solar power,Q_{conv} convective losses,Q_{rad} radiative losses to sky, and Q_{cond} conduction to mounting structures [7].

Convective heat loss follows

$$Qconv = hA(Ts - T\infty),$$

With h the convective coefficient, A the area, and T_∞ ambient air temperature [8]. In free convection behind tilted modules, hhh depends on Rayleigh and Nusselt numbers, with empirical correlations of the form

$$Nu = CRenPrm,$$

which are standard in the heat-transfer literature [9]. Increasing R_e (by inducing airflow) or enlarging A (by fins) raises N_u and thus h, lowering cell temperature [10].

Radiative losses to the sky can be estimated by

$$Q_{rad}=\varepsilon\sigma A(T_s^4 - T_{sky}^4),$$

where ε is mid-IR emissivity and σ the Stefan–Boltzmann constant [11]. Selectively enhancing ε in the atmospheric window (8–13 μm) while minimizing solar absorptance forms the basis of modern daytime radiative coolers [12].

2.2. Material thermal conductivity and spreading

Thermal gradients across the laminate lead to hot spots and reliability risks. High-conductivity backsheets, thermally conductive adhesives, and graphene-enhanced thermal interface materials can improve lateral heat spreading. Effective conductivity of composite layers can be estimated as

$$k_{eff}=k_f(1+\phi\beta)$$

for nanofilled media, where k_f is the base conductivity, ϕ the filler fraction, and β an empirical enhancement factor [13].

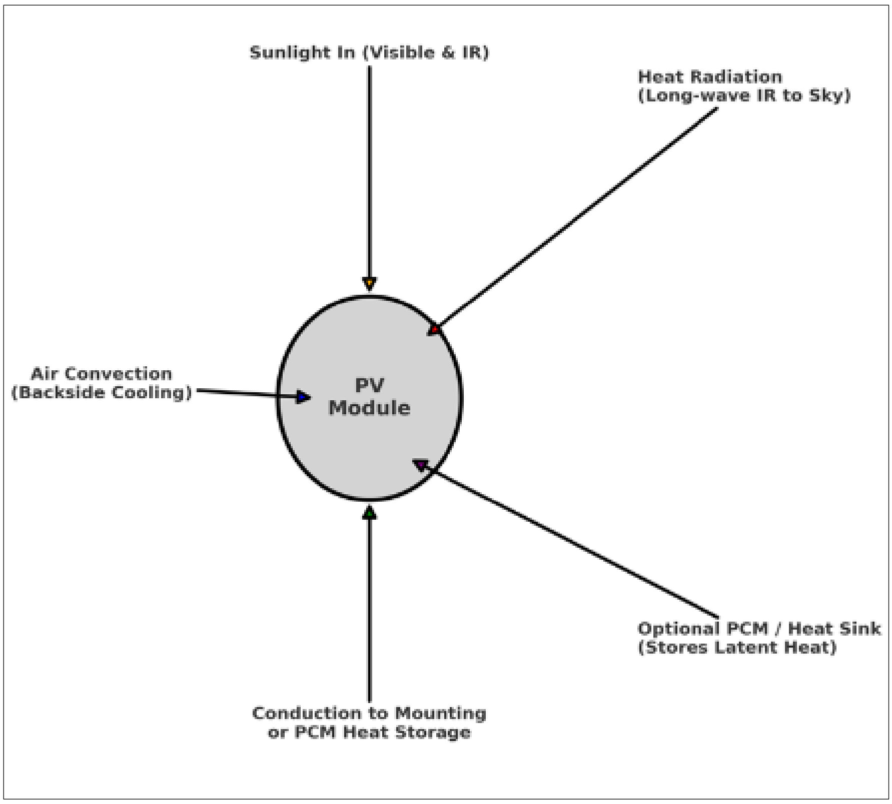

Figure 1 Conceptual diagram of heat transfer pathways in a photovoltaic module (self-designed by the authors)

This figure illustrates the main heat-transfer mechanisms affecting a photovoltaic module. Incoming solar irradiance (orange arrow) heats the cell layer. Part of the heat is dissipated by radiative emission (red arrow) in the mid-infrared window toward the sky, while convective airflow behind the module (blue arrows) carries heat away by natural or forced convection. At the same time, conduction transfers heat downward to the mounting structure or into a phase-change material (PCM) layer for latent-heat storage (green and purple arrows). By managing these pathways—through enhanced back ventilation, radiative coatings, and PCMs—the module's operating temperature can be reduced, improving electrical efficiency, lifetime, and lowering life-cycle greenhouse gas emissions.

3. Passive cooling strategies

3.1. Rear-side convection and finned backsheets

Rear cavities and stand-off distances create buoyancy-driven flow. Modeling and experiments show that a 10–15 cm air gap behind modules can lower cell temperature by 5–10 °C under typical summer conditions [5][8]. Adding aluminum fins or heat pipes to the backsheet increases the effective area AAA and reduces the thermal resistance. This approach mirrors finned-tube heat exchangers, using low-cost, durable components compatible with mass production [14][15].

3.2. Phase-change materials (PCMs)

PCMs such as paraffins or salt hydrates absorb large amounts of heat during phase transition, limiting the midday temperature spike. Studies in hot climates report module temperature reductions of 5–15 °C and electrical efficiency gains of 1–3 % when PCM melting points are tuned to local peak temperatures [6][13][16]. However, low thermal conductivity of pure PCMs necessitates enhancements like metal foams or nanoparticle doping, as captured in the keffk_\text{eff}keff expression above. Long-term performance depends on maintaining full solidification overnight and avoiding leakage or chemical degradation [17][18].

3.2.1. Case Study: PCM Integration in Hot-Arid Climates

A practical example of thermal management effectiveness is reported by Phukaokaew et al. [13], who tested a crystalline-silicon PV module integrated with a paraffin-based phase-change material (PCM) in a hot-arid environment. Their field measurements showed that the PCM reduced peak module temperature by 10–12 °C compared to an unmodified reference panel during midday conditions (ambient ≈38 °C). This temperature reduction translated into an electrical efficiency gain of about 2 % and a significant decrease in backsheet strain, implying improved long-term reliability. Tang et al. [14] confirmed similar behavior across multiple climate zones, noting that modules with PCM layers maintained 5–15 °C lower temperatures and exhibited slower power degradation over repeated thermal cycles. Together, these studies demonstrate that PCM integration can deliver measurable sustainability benefits, especially in regions with high solar irradiance and large diurnal temperature swings.

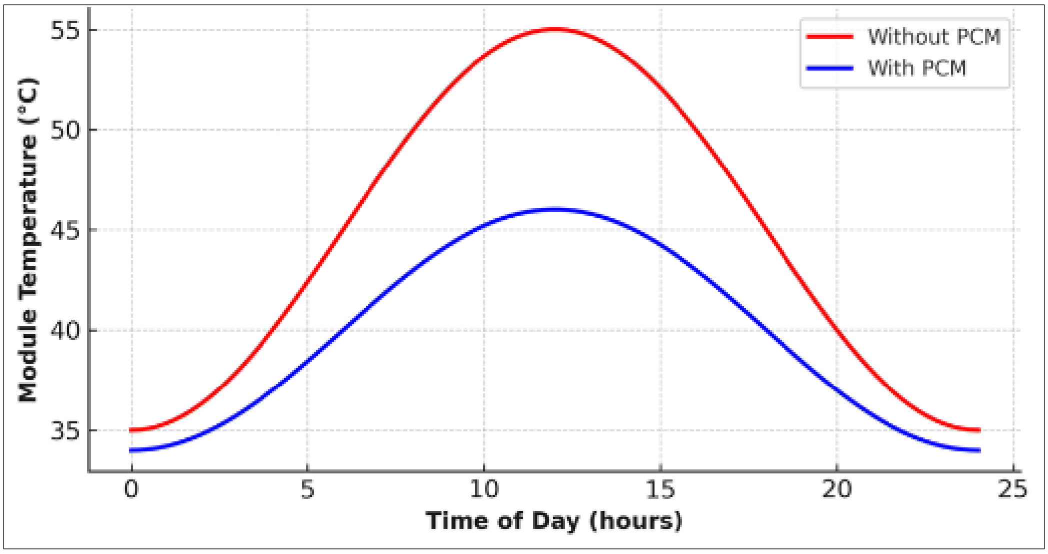

Figure 2 Effect of PCM on PV module temperature (schematic illustration, self-designed by the authors)

This figure shows the diurnal temperature profile of a photovoltaic module with and without an integrated phase-change material (PCM). The red curve (without PCM) illustrates a typical temperature rise around midday, while the blue curve (with PCM) demonstrates how latent-heat absorption reduces the peak temperature and flattens the thermal profile. Such reductions improve module efficiency and slow down material degradation over time.

3.3. Radiative cooling coatings

Daytime radiative cooling (DRC) exploits surfaces with high reflectance in the solar spectrum and high emissivity in the atmospheric window. Breakthrough demonstrations have achieved several degrees sub-ambient cooling at noon on vertical and horizontal surfaces [12][19]. Integration with PV modules requires maintaining optical transmission to the cell while adding the emissive layer to the backsheet or a separate radiator. Angular response, UV stability, and soiling resistance are current research priorities [20].

3.3.1. Case Study: Daytime Radiative Cooling on Vertical PV Surfaces

Recent work by Xie et al. [7] demonstrated a spectrally selective daytime radiative cooling (DRC) coating applied to vertical photovoltaic (PV) façade panels. In a field experiment under peak solar irradiance (≈900 W/m^2) and ambient air temperatures of 35–37 °C, the coated panels achieved sub-ambient surface temperatures up to 4–6 °C below ambient during midday and maintained significantly lower cell temperatures (≈10 °C cooler than uncoated reference panels). Wu et al. [11] further showed that a dual-selective thermal emitter increased long-wave emissivity while maintaining low solar absorptance, enabling enhanced radiative heat rejection even on tilted or vertical modules. These demonstrations confirm that photonic coatings can provide measurable cooling benefits in real outdoor conditions, complementing convection and PCM strategies and extending module life in high-irradiance urban environments.

4. Hybrid and Active Cooling Approaches

4.1. Photovoltaic/Thermal (PV/T) collectors

PV/T modules circulate air or liquid directly behind the cells, extracting heat for domestic hot water or space heating while lowering cell temperature. Reviews report higher total exergy utilization and improved electrical performance relative to PV-only systems under load [17]. Nanofluid coolants (Al_2O_3-water, CuO-water) provide higher thermal conductivity and specific heat than plain water, further reducing PV temperature and increasing thermal energy yield [18].

4.2. PV–thermoelectric hybrids

Thermoelectric generators (TEGs) mounted on PV backsheets convert part of the temperature gradient into electricity while adding a heat sink. Spectral splitting—directing visible light to PV and IR to TEG—can enhance net gains. Recent analyses conclude that high-ZT materials and concentration are needed for meaningful power, but field trials are progressing [19][20].

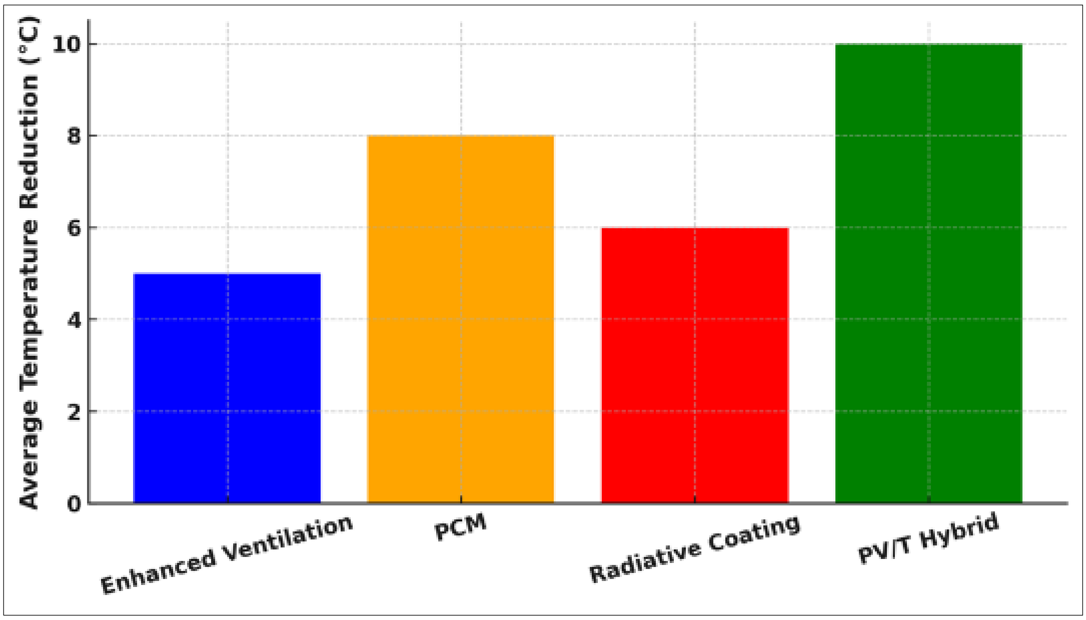

Figure 3 Comparative cooling performances of different techniques (self-designed by the authors)

Table 1 Table 1. Summary of cooling approaches for photovoltaic modules (compiled by the authors based on reviewed literature).

Technique	Cooling Mechanism	Typical Temperature Reduction (°C)	Electrical Efficiency Gain (%)	Key Advantages	Key Limitations
Enhanced Ventilation	Natural convection at rear side of module	3–6	0.5–1.0	Low cost, easy integration	Limited effect in very hot or low-wind conditions
PCM Layer	Latent heat storage behind module	5–15	1–3	Smooths midday temperature peaks, fully passive	Needs conductivity enhancement, overnight reset required
Radiative Coating	High mid-IR emissivity, low solar absorptance	4–8 (sub-ambient possible)	0.5–2	Works day and night, no moving parts	Requires UV stability and clean surfaces
PV/T Hybrid	Liquid/air circulation with heat recovery	8–12	1–4 plus usable heat	Displaces fossil heating load, increases exergy	Pumps, piping, higher cost/complexity
PV–TEG Hybrid	Thermoelectric generation from ΔT	up to 5 (still emerging)	0.5–1 extra	Adds electrical output from waste heat	High cost, low efficiency currently

This table summarizes the main passive and hybrid cooling approaches discussed in the review, including typical temperature reductions, electrical efficiency gains, advantages, and limitations.

5. Reliability, Soiling, and Desert Performance

Heat accelerates encapsulant browning, backsheet cracking, solder fatigue, and potential-induced degradation. Lowering module temperature therefore improves both immediate yield and long-term reliability [1][4]. Soiling adds an optical and thermal penalty, especially in desert regions; anti-soiling coatings paired with radiative or PCM cooling can reduce both dust deposition and temperature rise [16][20]. Large meta-analyses show that reducing average module temperature by a few degrees can extend the time to 80 % power retention by several years [3][4][15].

6. Sustainability and Life-Cycle Perspective

Life-cycle assessments consistently show that manufacturing energy and yield dominate PV's gCO_2-eq/kWh. Thus, any credible strategy that increases lifetime electricity production—through cooler operation, slower degradation, and co-generation of useful heat—reduces embodied emissions [3][4][17]. Integrating PV/T in particular displaces fossil-fuel heating, compounding the GHG benefit [17][18]. Harmonized inventories from IEA-PVPS Task 12 confirm these relationships across climates and technologies [3].

7. Future research directions

Future work should develop UV-stable, abrasion-resistant radiative coatings with high emissivity and color fidelity; recyclable, fire-safe PCMs with high thermal conductivity; and standardized outdoor protocols measuring electrical, thermal, and maintenance data over full year cycles. Bankable PV/T designs need validated fouling and cleaning economics. Techno-economic and LCA frameworks should explicitly value thermal-management co-benefits in gCO_2-eq/kWh [6][7][15]. Predictive controls using AI and weather forecasting could dynamically adjust ventilation and coolant flow to optimize real-time temperature and efficiency.

8. Conclusion

Heat-transfer engineering is not an ancillary concern but a core design parameter for sustainable PV. Combining buoyancy-driven rear-cavity flow and fins, PCM buffering of midday peaks, spectrally selective radiative cooling, and harvesting unavoidable heat with PV/T systems delivers more electricity for the same embodied footprint, extends lifetime, and lowers lifecycle GHG intensity. Recent photonic advances enabling sub-ambient cooling on vertical PV surfaces broaden options for façades, while careful PCM and PV/T integration delivers complementary gains in hot climates.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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