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Thermal Management of Photovoltaic Modules: Material Strategies and Structural Optimization

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Abstract

The industrialization of TOPCon and perovskite-silicon tandem solar cells has shifted photovoltaic thermal management from a one-size-fits-all cooling approach to customized strategies that target specific degradation mechanisms. In these advanced cells, high temperatures induce irreversible degradation—such as surface passivation degradation in TOPCon and halide ion migration in perovskite tandems—that cannot be reversed by simple temperature reduction. This review synthesizes current understanding of these degradation pathways and evaluates the design principles and durability of radiative cooling coatings, phase-change materials, and spectrally selective encapsulants. It further examines structural measures—including fractal fins, heat pipes, and array spacing optimization—that enhance heat dissipation. A quantitative framework integrating thermal, electrical, thermodynamic, and economic metrics with levelized cost of electricity (LCOE) is proposed to enable objective comparisons across climates and technologies. We argue that coordinated material–structure design offers the most promising route to overcoming performance bottlenecks and bridging the gap between laboratory breakthroughs and industrial deployment.

Keywords

photovoltaic thermal management, structural optimization, TOPCon solar cells, perovskite-silicon tandem solar cells

1. Introduction

As a central pillar of the energy transition, n-type crystalline silicon cells—represented by TOPCon and heterojunction technologies—currently dominate the market due to their high conversion efficiency. The 63rd edition of the solar cell efficiency table published by Green et al. [1] shows that the laboratory efficiency of TOPCon cells has exceeded 26%, while perovskite-silicon tandem solar cells have achieved a certified efficiency of over 34% through novel molecular interface engineering [2], establishing themselves as a next-generation disruptive technology platform. However, these high-efficiency battery systems exhibit significant differences in the irreversible degradation that occurs at high temperatures, and traditional thermal management strategies—which focus solely on “cooling”—are no longer sufficient to meet these demands.

In the crystalline silicon process, Ratnapagol et al. [3] found that the degradation and recovery of n+ poly-Si/SiOx junctions are thermally activated. Separately, Tong et al. [4] identified that sodium contamination accelerates chemical degradation of the rear SiNx layer in TOPCon cells, a mechanism referred to as surface passivation degradation (SPD). In addition, light and temperature-induced degradation (LeTID) and ultraviolet-induced degradation (UVID) accelerate irreversible degradation at high temperatures [5].

In perovskite-based tandem systems, rising temperatures significantly accelerate halide ion migration, inducing phase separation and lattice transitions, which cause a sharp drop in device efficiency and a deterioration in long-term stability [6].

Reversible transient power losses and irreversible degradation caused by high temperatures have shifted the research focus from simple passive cooling to customized thermal management strategies. These strategies primarily revolve around spectral modulation, phase-change energy storage, and biomimetic heat dissipation. In a systematic review published in 2025, Mazzeo et al. [7] point out that photovoltaic systems incorporating enhanced phase-change materials can significantly reduce module temperature and improve electrical efficiency. Integrating material-level thermal regulation with structural heat dissipation optimization is essential to overcome these bottlenecks.

This review bridges microscopic degradation mechanisms with macroscopic material–structure design, and establishes a quantitative evaluation framework coupling thermodynamic analysis with LCOE.

2. Mechanisms and evaluation framework for thermal effects in photovoltaic systems

2.1 Irreversible Degradation Mechanisms in High-Efficiency Batteries

The operating temperature of photovoltaic modules continues to rise due to the combined effects of optical and electrical losses. For conventional crystalline silicon modules, high temperatures cause reversible transient power losses. For new types of high-efficiency cells, such as TOPCon and perovskite stacks, high temperatures can cause irreversible degradation that cannot be self-recovered, which permanently degrades module performance.

TOPCon cell efficiency is reduced by various mechanisms. The IEA PVPS technical report [8] points out that SPD, UVID, and potential-induced degradation (PID) are currently the three most significant mechanisms affecting efficiency. Regarding SPD, Tong et al. [4] found that sodium salt contamination significantly accelerates the chemical degradation of the SiNx layer on the back of TOPCon cells under hot and humid conditions, resulting in a significant loss of open-circuit voltage. With regard to UVID, a study by Khan et al. [5] found that storing samples in the dark at room temperature after UVID testing actually leads to the continued accumulation of degradation in the passivation layer.

For perovskite–silicon tandems, rising temperatures accelerate halide ion migration, inducing phase segregation and lattice distortion that permanently degrade device efficiency [6]. Consequently, thermal management is particularly critical for these stacked structures.

2.2 Thermal Management Performance Evaluation System

To enable an objective comparison of different thermal management strategies, this paper establishes a multi-dimensional evaluation framework that spans thermal, electrical, thermodynamic, and economic performance criteria (Table 1).

At the thermal level, the temperature drop (ΔT) and the temperature uniformity coefficient (σ_T) are adopted as primary metrics. These parameters not only quantify the instantaneous reversible efficiency loss but also directly correlate with hotspot risks and thermomechanical stress within the encapsulation layer, which are critical for long-term reliability. At the electrical level, the equivalent efficiency gain ($\Delta\eta_{eq}$) is introduced, which converts the measured ΔT into a percentage efficiency improvement using the cell's temperature coefficient β, which removes variability from irradiance and ambient conditions and allows cross-study comparison.

For degradation-sensitive cells, however, additional metrics are needed. For TOPCon devices that are prone to surface passivation degradation (SPD), the Open Circuit Voltage Retention (V_{ocR}) is incorporated as a key indicator. Unlike conventional efficiency metrics, V_{ocR} specifically captures the suppression of irreversible degradation, thereby distinguishing mere temperature reduction from genuinely protective thermal management.

From an economic standpoint, thermal management measures influence the levelized cost of electricity (LCOE) by balancing extra capital cost against higher energy yield. As noted by Prilliman et al. [9], optimizing array spacing to enhance convective cooling can be economically viable in regions with favorable wind and temperature conditions. With the continuing decline in PV module prices, LCOE-based optimization is becoming increasingly decisive for selecting appropriate strategies across different climatic zones.

Table 1: Quantitative evaluation framework for photovoltaic thermal management

Evaluation Dimensions	Core Metrics	Calculation Method/Definition	Use Cases Related to Batteries
Thermal Properties	Temperature drop ΔT	$\Delta T = T_{ref} - T_{managed}$ T_{ref} is Average Temperature in the Reference Group, $T_{managed}$ is Average Temperature in the Managed Group	General metrics that directly determine the magnitude of reversible efficiency loss
	Temperature Uniformity σ_T	$\sigma_T = \sqrt{(1/N \cdot \Sigma(T\_i - \bar{T})^2)}$ Standard deviation of the temperature distribution on the component surface	Correlation between Hotspot Risk and thermomechanical stress in the encapsulation layer; sensitivity to localized SPD in TOPCon
Electrical Performance	Equivalent Efficiency Gain η_{rec}	$\eta_{rec} = \beta \cdot \Delta T$ β is Battery Temperature Coefficient	Universal metrics that eliminate differences in irradiation and environmental conditions to enable cross-strategy comparability
	Open Circuit Voltage Retention V_{ocR}	$V_{ocR} = V_{oc}(t) / V_{oc}(0)$ 100% Open-Circuit Voltage Ratio After Damp-Heat Aging	Specifically designed for SPD-sensitive cells such as TOPCon; distinguishes between simple cooling and the suppression of irreversible degradation
Thermodynamics Properties	Energy Efficiency η_{ex}	$\eta_{ex} = E_{out} / E_{in}$ $Ex_d = T_0 \cdot S_{gen}$ T_0 is Ambient Temperature	The system identifies key areas of energy loss and prioritizes optimization of stages with significant energy loss.
Economic Feasibility	LCOE Growth Rate δ_{LCOE}	$\delta_{LCOE} = (LCOE_{managed} - LCOE_{ref}) / LCOE_{ref} \times 100\%$ Considering Additional Costs and Power Generation Gains	Key indicator that is particularly sensitive in high-temperature, high-radiation areas such as plateaus and deserts
	Payback Period PBP	$PBP = C_{add} / \Delta R_{annual}$ C_{add} is Additional Investment in Thermal Management ΔR_{annual} is Annual Incremental Revenue from Electricity Generation	Supplementary indicators; strategies with high additional costs, such as PCM, require careful evaluation

3. A Review of Strategies for Thermal Management Materials

3.1 Radiative Cooling Coatings

Radiative Cooling (RC) radiates heat into the cold space through the 8–13 μm atmospheric transparent window while reflecting solar radiation to reduce heat absorption. The core challenge in photovoltaic applications is that solar cells need to fully utilize photons in the visible and near-infrared regions of the spectrum for photovoltaic conversion, while cooling requires reflecting some of the incident light to reduce temperature rise.

To address this conflict, research is advancing in two directions. First, back-side radiative cooling coatings optimize solar reflectance without interfering with front-side light absorption. Second, transparent radiative cooling layers are being developed to achieve selective emission in the mid-infrared band while maintaining high visible light transmittance.

Outdoor applications of radiative cooling coatings face multiple challenges, including UV aging, dust accumulation, and mechanical wear. Toughening strategies include fully inorganic ceramic films and graded porous coatings, both of which improve UV durability. Yet scaling up production and controlling cost remain unresolved.

3.2 Phase-Change Energy Storage Materials

Phase Change Materials (PCMs) utilize the property of absorbing or releasing large amounts of latent heat during phase transitions to passively regulate component temperature. PCMs used for photovoltaic temperature control primarily fall into two categories: organic PCMs and inorganic hydrated salts.

Mazzeo et al. [7] highlight that PCM-based cooling is constrained by low thermal conductivity—which limits transient response—and by microcracking that compromises material integrity. Little is known, however, about PCM aging under the humid-heat conditions typical of fielded modules; high-humidity environments may accelerate performance degradation through mechanisms such as moisture penetration and filler hydrolysis.

3.3 Spectrally Selective Encapsulation Materials

The encapsulation film is a critical component in the thermal resistance chain of photovoltaic modules, and its optical stability directly determines the long-term performance of the cells. Ethylene-vinyl acetate (EVA), commonly used in the market today, is prone to photolysis under high-temperature, high-humidity conditions and UV exposure, producing acetic acid, which leads to corrosion of metal grid lines, module delamination, and potential-induced degradation (PID). Polyolefin elastomers (POE) and thermoplastic polyolefins (TPO) have garnered significant attention as alternative materials: POE offers superior moisture barrier properties and PID resistance, while TPO features shorter lamination times, lower energy consumption, and better recyclability [8].

For UVID-sensitive cells such as TOPCon, the UV-blocking performance of encapsulation materials is critical. Khan et al. [5] found that adjusting the UV cutoff wavelength of the encapsulation film can effectively reduce the severity of UVID. To mitigate this, UV down-shifting encapsulants convert UV photons to the visible light region, thereby avoiding the risk of degradation associated with traditional UV absorbers while contributing additional usable photons to the cell. This technology has already been applied in SHJ module designs and offers a practical route to suppressing UVID in TOPCon cells [8].

4. Heat Dissipation Structures and Geometric Optimization

4.1 Geometric Optimization of Passive Cooling Structures

Fins are the most classic and widely used passive heat dissipation structures; they enhance heat transfer on the back side of components by increasing the convective heat transfer area. Traditional straight fins suffer from thermal boundary layer thickening and insufficient space utilization. Cutting-edge research is addressing these bottlenecks through innovations in geometric topology and biomimetic design.

In the field of fractal geometric design, Du et al. [10] experimentally investigated the thermal performance of a photovoltaic–phase change material system equipped with Cantor fractal fins and compared them with conventional rectangular fins of equal volume. Their results showed that the fractal arrangements significantly improved temperature uniformity and heat transfer rates, achieving a maximum wall temperature drop of 9.1 °C. This topology mimics the self-similar branching of leaf veins, maximizing surface area without sacrificing compactness [10].

Heat pipes utilize the phase-change cycle of the working fluid to achieve highly efficient heat transfer far exceeding pure metal thermal conduction, providing an ideal solution to heat accumulation. While a single heat pipe suffers from insufficient heat transfer efficiency under low heat flux density conditions, coupling it with a phase-change material (PCM) compensates for this shortcoming. The heat pipe rapidly transfers heat to the PCM’s thermal storage chamber, while the PCM buffers transient thermal peaks, achieving a synergistic effect that combines fast response with high thermal capacity.

4.2 Installation Architecture and Environment Coupling

The heat dissipation capacity of photovoltaic modules is closely related to installation factors such as the mounting angle, rear ventilation gaps, and array layout. In Building-Integrated Photovoltaics (BIPV) and rooftop installation systems, the air gap between the backplate and the wall or roof surface forms a natural convection channel, and its geometric dimensions have a decisive impact on cooling performance. The convective heat transfer coefficient for naturally ventilated BIPV systems can be estimated using an optimized Nusselt number correlation, and a properly designed air gap can significantly reduce the operating temperature of the modules [8].

In large-scale photovoltaic power plants, row spacing affects both land use and array-level cooling. Dense layouts obstruct downward airflow, trap hot air, and raise inner-module temperatures. In regions with low average annual temperatures and medium-to-high average annual wind speeds, adjusting the row spacing to improve convective cooling makes a particularly significant contribution to reducing the LCOE.

4.3 Material–Structure Co-Design

Radiative cooling coatings, phase-change energy storage materials, and finned structures each have their own optimal operating ranges and inherent limitations; thus, no single technology can satisfy all operating conditions. The synergistic optimization of materials and structures is increasingly recognized as the key to overcoming performance limitations.

Radiative cooling and induced ventilation can be used in conjunction. Radiative cooling coatings reduce the incident heat load and lessen the intensity of convective heat dissipation; at the same time, induced ventilation at the rear rapidly displaces the hot, humid air that accumulates around the modules, thereby reducing the interference of the wet film on the emission spectrum.

Multiphysics models that couple optical, thermal, electrical, and mechanical effects predict thermomechanical stress, microcrack propagation, and delamination under damp-heat aging, and support parameter optimization in material–structure co-design.

Overall, material–structure co-design is a key approach to advancing the practical application of thermal management for next-generation, efficient, stable photovoltaic systems. Future research should focus on establishing standardized co-design processes and developing accelerated aging test protocols that cover the entire life cycle, thereby enabling a rapid transition from laboratory innovation to industrial application.

5. Conclusion

This paper provides an overview of photovoltaic modules, ranging from microscopic heat generation to macroscopic structural design. Single-strategy cooling fails to address cell-specific degradation such as passivation degradation in TOPCon and thermal decay in perovskites. The synergistic integration of radiative cooling, phase-change energy storage, and optimization measures such as fins and heat pipes can enhance cooling performance and stabilize the photovoltaic conversion system. The evaluation framework established in this paper yields a benchmark for comparing climates and technologies, and guides the commercialization of next-generation high-efficiency systems.

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