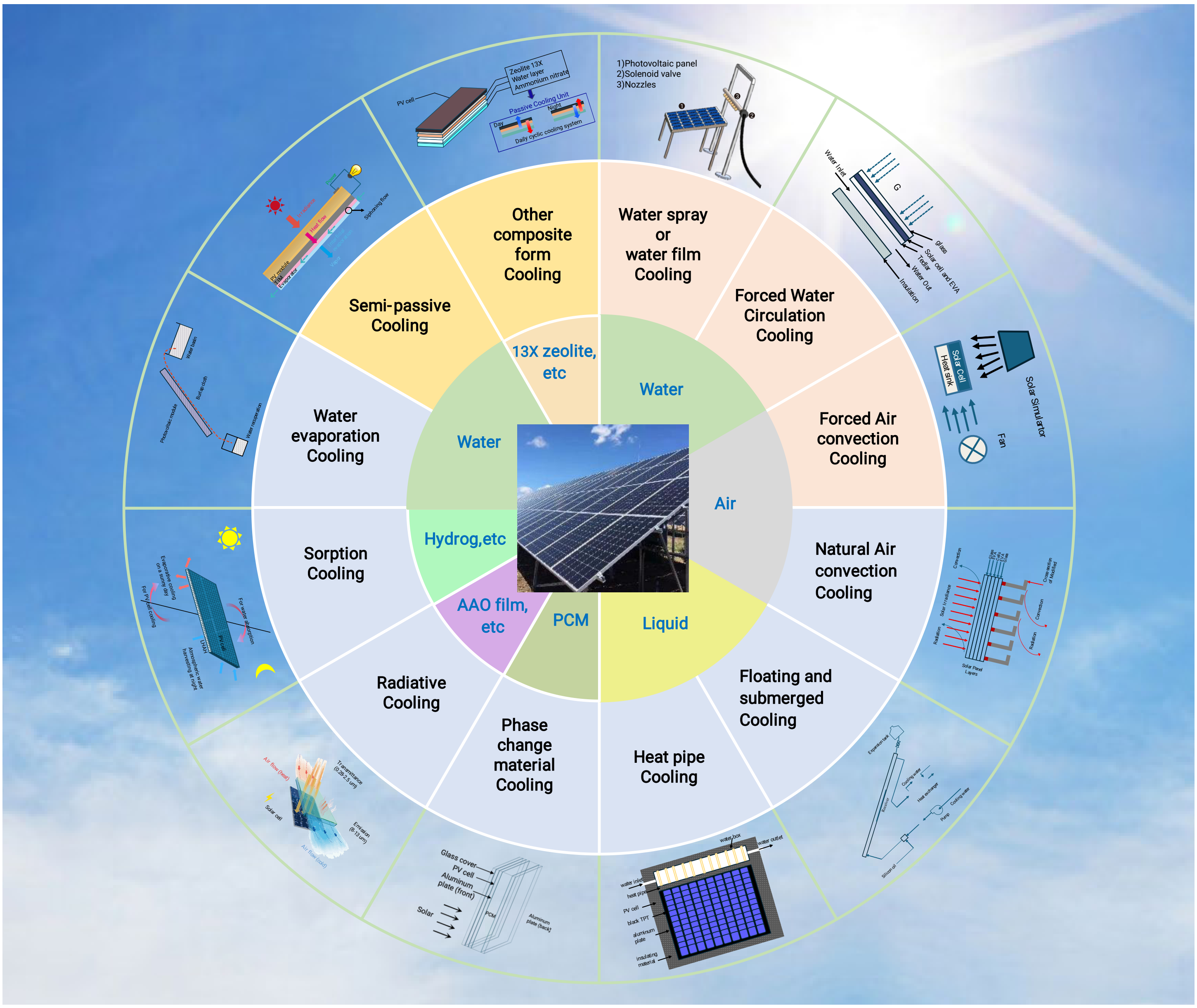
# Engineering-oriented review of photovoltaic cooling technologies: From performance metrics to strategy selection

**Qianqian Jin,**[1,2] **Ming Yan,**[1,2] **Chong Zhai,**[1,2,*] **and Chenhan Liu**[1,2,*]
*Correspondence: zhaichong@nnu.edu.cn (C. Z.); chenhanliu@njnu.edu.cn(C. L.)
Received: March 27, 2026; Accepted: April 20, 2026; Published Online: April 23, 2026; https://doi.org/10.59717/j.xinn-energy.2026.100158


## GRAPHICAL ABSTRACT




## PUBLIC SUMMARY

- This review synthesizes PV cooling technologies from an engineering and deployment perspective.
- Cooling methods are categorized into active, passive, environment-driven, and hybrid approaches.
- Strategies are compared using unified metrics: cooling effect, energy gain, resource use, and reliability.
- A decision framework links cooling choices to climate, installation constraints, and system goals.
- PV cooling is framed as a multi-objective design problem for scalable and sustainable applications.

# Engineering-oriented review of photovoltaic cooling technologies: From performance metrics to strategy selection

Qianqian Jin,[1,2] Ming Yan,[1,2] Chong Zhai,[1,2,*] and Chenhan Liu[1,2,*]

[1]School of Energy and Mechanical Engineering, Nanjing Normal University, Nanjing 210023, China

[2]Advanced Thermal Management Technology and Functional Materials Laboratory, Nanjing Normal University, Nanjing 210023, China

*Correspondence: zhaichong@nnu.edu.cn (C. Z.); chenhanliu@njnu.edu.cn(C. L.)

Received: March 27, 2026; Accepted: April 20, 2026; Published Online: April 23, 2026; https://doi.org/10.59717/j.xinn-energy.2026.100158



Citation: Jin Q., Yan M., Zhai C., et al. (2026). Engineering-oriented review of photovoltaic cooling technologies: From performance metrics to strategy selection. *The Innovation Energy* **3**:100158.

The operating temperature of photovoltaic (PV) modules strongly affects electrical efficiency, reliability, and lifetime, yet existing thermal management solutions remain fragmented and difficult to translate into practical deployment. This review presents an engineering-oriented synthesis of PV cooling technologies, shifting the focus from isolated temperature reduction to system-level performance, deployability, and sustainability. Cooling strategies are systematically categorized into active, passive, environment-driven, and hybrid approaches, and evaluated using unified metrics including temperature reduction (typically ~3–50 °C), net energy gain (up to ~25% under favorable conditions), parasitic energy consumption, resource footprint, reliability, and technology readiness level (TRL 2–8).Based on this systematic categorization and evaluation, a decision-oriented cooling strategy selection framework is proposed to bridge the gap between laboratory-scale demonstrations and real-world deployment by linking climate conditions, installation constraints, and system objectives with scenario-matched cooling solutions. By explicitly addressing the fragmented nature of existing studies, this work reframes PV cooling as a multi-objective engineering design problem rather than a single-metric optimization task. The proposed framework provides actionable guidance for selecting and integrating cooling strategies across diverse PV applications and highlights future directions toward scalable, reliable, and resource-efficient photovoltaic thermal management.

## INTRODUCTION

The global energy system is undergoing an accelerated transition to mitigate climate change and achieve sustainable development. The continued reliance on fossil fuels has intensified greenhouse gas emissions and exacerbated energy and environmental challenges.[1] In response, China has committed to peaking carbon emissions by 2030 and achieving carbon neutrality by 2060,[2] highlighting the urgent need for large-scale deployment of renewable energy. Among available options, solar energy—particularly photovoltaic technology—has emerged as a cornerstone of decarbonization due to its abundant resources, scalability, and rapidly expanding global adoption.[3-5]

Photovoltaic (PV) modules convert solar radiation into electricity through the photovoltaic effect, wherein photons with energy exceeding the semiconductor bandgap generate electron-hole pairs, producing a direct current via the built-in electric field of PN junctions.[6,7] However, this energy conversion process is inherently inefficient, with only 15–24% of absorbed solar energy converted to electricity.[8,9] The electrical performance of PV modules is strongly coupled with operating temperature, and excessive heat accumulation on the cell surface is widely recognized as a key bottleneck limiting energy yield and long-term reliability. Under high solar irradiance and elevated ambient temperature, the PV cell temperature can significantly exceed the surrounding environment, leading to notable power losses, accelerated material degradation, and increased risks of hot-spot formation and performance mismatch within the module string.[10,11]

To address this challenge, a broad spectrum of PV cooling approaches has been proposed and demonstrated over the past decades. These approaches can be generally grouped into passive cooling (e.g., enhanced convection, heat sinks, phase change materials, radiative cooling coatings),[12-14] active cooling (e.g., forced air or liquid circulation, spray/evaporative cooling),[12-22] and hybrid cooling architectures that combine multiple mechanisms or integrate PV cooling with energy cascading and smart control. While substantial progress has been made, PV cooling remains far from a "one-solution-fits-all" technology. In practice, the effectiveness and feasibility of any cooling strategy is highly scenario-dependent, constrained by local climate, water availability, allowable auxiliary power, and operation and maintenance requirements.

Despite the rapid development of diverse PV cooling concepts, the practical deployment of cooling technologies is inherently scenario-dependent and strongly constrained by real-world engineering conditions. In many cases, an effective cooling method at the laboratory scale does not necessarily translate into a scalable and sustainable solution in the field, because the overall benefit must be evaluated at the system level rather than by temperature reduction alone. A comprehensive assessment should simultaneously account for the net energy gain after auxiliary power consumption, the long-term sustainability associated with water use, and the reliability risks introduced by additional components such as pumps, fans, piping, or coatings. Furthermore, the feasibility of a given approach is closely linked to installation configuration and application context, where rooftop PV, building-integrated photovoltaics (BIPV) façades, utility-scale PV farms, floating PV systems, and CPV modules impose fundamentally different requirements on maintenance accessibility, cost tolerance, durability, and safety.

These coupled considerations indicate that PV cooling should be treated as a multi-objective engineering design and selection problem, where thermal enhancement, resource footprint, economic viability, and operational robustness must be balanced to achieve deployable and long-lasting performance improvement. Therefore, a high-impact review should not only summarize cooling technologies but also provide a decision-oriented framework enabling practitioners to translate reported laboratory achievements into actionable deployment strategies.[23] Early works[24-26] focus narrowly on specific cooling modalities or fail to incorporate recent advancements. More recent syntheses[27,28] concentrate on binary classifications (active/passive) without addressing hybrid systems or emerging materials.

To bridge the gap between fragmented laboratory demonstrations and real-world deployment, this review provides an engineering-oriented synthesis of PV cooling technologies. Specifically, we provide:

1. a structured and updated overview of PV cooling technologies across passive, active, and hybrid categories.

2. a system-level synthesis of key trade-offs using unified metrics including temperature reduction, efficiency gain, auxiliary power ratio, water footprint, durability, and technology readiness.

3. a decision-oriented selection framework (Figure 1) that explicitly links climate conditions and installation constraints to scenario-matched cooling solutions.

By reframing PV cooling as a multi-objective engineering design problem, this work delivers actionable guidance for practitioners and outlines a roadmap toward scalable, reliable, and resource-efficient photovoltaic thermal management.

Despite extensive efforts to enhance photovoltaic cooling performance, existing studies often compare cooling techniques using isolated metrics, such as peak temperature reduction or instantaneous efficiency improvement. However, in practical applications, cooling effectiveness emerges from the combined influence of thermal driving forces, system configuration, and resource inputs.[29,30] As illustrated in Figure 2, representative cooling strategies, spanning active, passive, and hybrid approaches, exhibit substantial

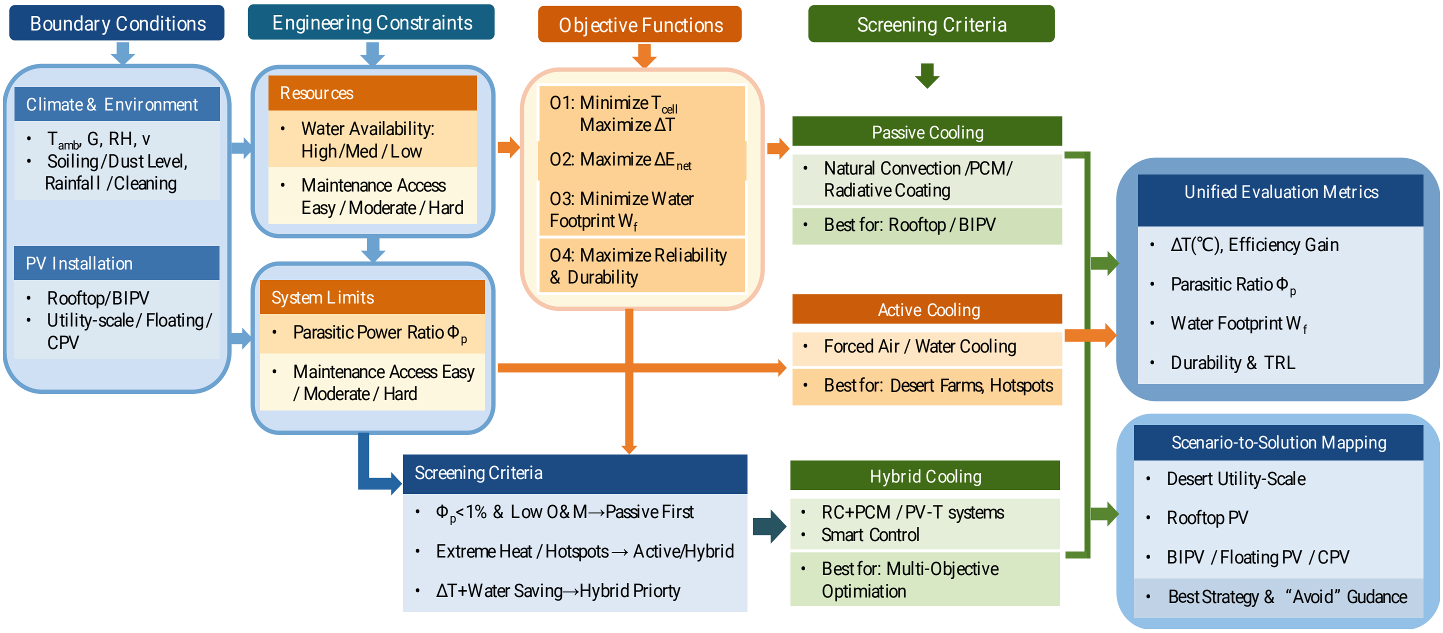



**Figure 1. PV Cooling Strategy Selection Framework: Decision-oriented architecture selection under multi-factor constraints**

overlap in their achievable temperature reduction and cooling intensity. This dispersion indicates that no single cooling paradigm consistently outperforms others across all operating regimes. Instead, cooling strategies occupy distinct yet intersecting engineering design spaces, shaped by trade-offs among performance, complexity, and sustainability. These observations further motivate the need for a system-level, scenario-aware framework to guide the rational selection and integration of PV cooling technologies.

The remainder of this review is organized as follows. Section 2 presents an overall classification of PV cooling strategies and introduces unified system-level evaluation metrics to support engineering-oriented comparison. Section 3 reviews active cooling approaches, with emphasis on their cooling effectiveness, auxiliary energy consumption, and operational feasibility. Section 4 summarizes passive cooling methods, highlighting material-driven thermal regulation, radiative/convection enhancement mechanisms, and long-term reliability considerations. Section 5 focuses on hybrid cooling architectures and emerging trends and further provides scenario-to-solution mapping and future research roadmaps toward scalable, durable, and resource-efficient PV cooling deployment. Finally, Section 6 concludes the review with key findings and outlook.

## ENGINEERING-ORIENTED OVERVIEW OF PV COOLING STRATEGIES

### PV thermal challenges and system-level impacts

Photovoltaic modules operate under continuous solar irradiation, where only a fraction of the absorbed energy is converted into electricity while the remaining portion is inevitably dissipated as heat.[31,32] As a result, PV cells typically experience a pronounced temperature rise above ambient conditions, especially under high irradiance, weak convective heat transfer, and limited rear-side ventilation. This thermal accumulation leads to elevated operating temperatures ($T_{cell}$), which fundamentally alters the electrical behavior of the semiconductor junction and introduces a persistent performance penalty during real-world operation.[33-37] In general, the electrical efficiency of crystalline silicon PV decreases with increasing cell temperature due to the reduction of open-circuit voltage, causing measurable power losses during peak solar hours and throughout hot seasons.[38,39] Therefore, PV cooling is not merely an auxiliary enhancement, but an essential pathway to stabilizing power output and maximizing energy yield over the lifetime of PV systems.

Beyond instantaneous efficiency loss, excessive module temperature can trigger a series of system-level reliability issues that directly influence long-term energy production and economic viability. Elevated thermal stress accelerates material aging in encapsulants and backsheets, enhances thermo-mechanical fatigue at interconnects and solder joints, and increases the likelihood of microcracks and contact degradation.[40] In addition, temperature non-uniformity across the PV surface can induce electrical mismatch within strings, producing localized overheating and increasing the risk of hot-spot formation. Such hot-spots not only reduce the effective output of the affected modules but may also compromise safety and shorten service life.[41-44] These degradation mechanisms indicate that thermal management should be evaluated not only by its ability to reduce average cell temperature, but also by its capability to suppress temperature gradients and improve thermal uniformity under fluctuating outdoor conditions.[45,46]

From an engineering standpoint, the impacts of PV thermal behavior are further amplified when PV systems are integrated into diverse deployment scenarios such as rooftop arrays, building-integrated photovoltaics (BIPV), utility-scale power plants, floating PV, or concentrated photovoltaics (CPV). These applications impose distinct boundary conditions and operational constraints, including different airflow patterns, installation geometries, allowable added weight, accessibility for maintenance, and exposure to dust, humidity, or salt spray. Consequently, a cooling strategy that performs well in controlled experiments may not deliver consistent or scalable benefits in the field unless it is designed to accommodate real-world variability and durability requirements. This motivates a system-level perspective for PV cooling, where the objective extends beyond maximizing temperature reduction to achieving net energy gain, operational robustness, and long-term reliability under practical constraints.[47] Such a perspective provides the foundation for developing engineering-oriented cooling selection frameworks and unified evaluation metrics in the subsequent sections.

### Classification of PV cooling strategies

To structure the rapidly growing PV cooling literature and enable engineering-oriented comparison, PV cooling strategies are broadly classified into passive cooling, active cooling, and hybrid cooling architectures. This taxonomy not only reflects differences in heat transfer mechanisms, but also captures their practical distinctions in resource dependence, operational complexity, and deployment feasibility under real-world constraints.

Passive cooling enhances heat dissipation without external energy input or consumables during operation, including natural convection enhancement, thermal spreading structures, phase change materials (PCMs), and radiative cooling coatings/films. Passive solutions are attractive for their near-zero parasitic power and simple integration, but their effectiveness is often sensitive to climate and installation conditions. Active cooling employs externally driven processes, such as forced air, liquid circulation, and spray/evaporative

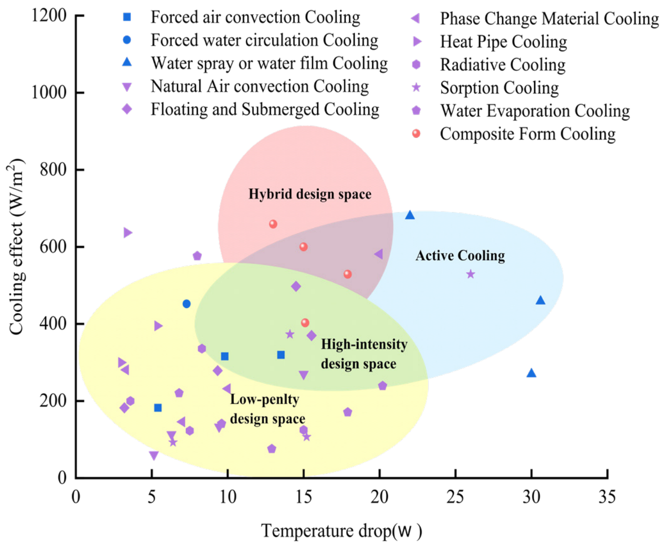



**Figure 2. Distribution of representative photovoltaic (PV) cooling strategies in terms of achievable temperature reduction and effective cooling intensity**

cooling, typically achieving stronger temperature suppression and improved controllability, while introducing auxiliary power consumption and additional reliability risks. Hybrid cooling combines multiple mechanisms to balance cooling effectiveness, parasitic penalties, resource footprint, and long-term robustness, offering flexible pathways for scenario-specific deployment but with increased integration complexity.

It is worth clarifying the position of environment-driven strategies within this taxonomy. While fundamentally passive in their zero-energy-input operation, they are distinguished here from structural and phase-change-based passive methods by their direct reliance on external environmental thermodynamic potentials-namely, the cold sky for radiative cooling, ambient humidity gradients for sorption cooling, and proximate water bodies for floating/submerged systems-as the primary heat sink. This distinction highlights their pronounced climate-dependent deployability and justifies their separate treatment. Environment-driven mechanisms also serve as foundational elements in hybrid architectures, where they are synergistically coupled with active or adaptive components to enhance overall system resilience and performance.

This classification provides the organizational backbone for the subsequent sections and supports system-level assessment using unified metrics, enabling consistent comparison and decision-oriented selection across diverse PV applications.

## Unified evaluation metrics for engineering comparison

A major challenge in the PV cooling literature is the lack of unified evaluation criteria, as reported performance is often obtained under different boundary conditions, test durations, and measurement standards. Consequently, direct cross-study comparison can be misleading if conclusions are drawn solely from temperature reduction or instantaneous electrical efficiency enhancement. From an engineering deployment perspective, PV cooling should be evaluated as a system-level improvement strategy rather than an isolated heat transfer enhancement technique.

In particular, cooling strategies should be assessed using metrics that capture both the magnitude and quality of thermal regulation. Besides the average temperature reduction (\Delta T), peak temperature suppression and temperature uniformity are important indicators because thermal non-uniformity may induce mismatch losses and increase hot-spot risk. The electrical benefit should be expressed not only by instantaneous output gains but also, when possible, by energy-yield-oriented indicators over representative timescales, which better reflect realistic operating performance under fluctuating outdoor conditions.

For active and hybrid cooling systems, penalty terms must be explicitly included to avoid overestimating their net benefits. Auxiliary power consumption and the parasitic power ratio is presented as：

$$\varnothing_p = \frac{P_{aux}}{P_{out}} \tag{1}$$

where $P_{aux}$ is the auxiliary power required to operate the cooling system and $P_{out}$ is the PV electrical output. It provides practical screening indicators, while water consumption should be quantified for spray/evaporative approaches to reflect sustainability constraints. In addition, reliability, O&M burden, scalability, and technology readiness level (TRL) are essential to evaluate long-term performance retention and deployment feasibility. Based on these considerations, Table S1 summarizes the unified system-level metrics adopted throughout this review to enable consistent engineering comparison of passive, active, and hybrid PV cooling solutions.

To enable consistent engineering comparison across studies, the above metrics are used to assess passive, active, and hybrid cooling approaches under different deployment constraints. When quantitative data are unavailable, qualitative levels (e.g., low/medium/high) are adopted to summarize O&M burden, complexity, and scalability, while highlighting key risks and boundary-condition dependence.

## Deployment constraints and boundary conditions

The effectiveness and feasibility of PV cooling strategies are strongly constrained by deployment boundary conditions, which often determine whether laboratory-level performance can be translated into consistent field benefits. In real outdoor environments, PV modules are subject to coupled influences from solar irradiance, ambient temperature, wind conditions, humidity, sky radiative properties, and contamination such as dust or salt spray. These factors alter both the thermal load and the dominant heat dissipation pathways, resulting in significant variability in cooling outcomes across different regions and operating seasons.

Climate conditions impose direct limitations on cooling mechanisms. High ambient temperatures (typically exceeding 35 °C) and strong irradiance (e.g., >800 W $m^{-2}$) substantially increase the demand for cooling capacity, whereas wind and airflow patterns regulate convective heat transfer on the module surfaces.[48,49] Humidity exerts a pronounced influence: evaporative cooling efficiency declines markedly when relative humidity exceeds 70% due to suppressed vapor pressure gradients, while water-involved systems face elevated corrosion risks in humid or saline environments. Radiative cooling performance, conversely, is highly sensitive to atmospheric transparency and can be severely attenuated under humid conditions (e.g., precipitable water vapor >3 cm) or overcast skies.[30]

Deployment constraints also depend on PV system type and installation layout. Rooftop PV and BIPV commonly face restrictions in mass, thickness, aesthetics, and rear-side ventilation, whereas utility-scale PV farms require scalable and low-maintenance solutions due to the large number of modules. Floating PV introduces continuous moisture exposure, and CPV systems experience intensified heat flux that demands robust thermal management. In addition, active cooling strategies may suffer from parasitic power penalties, and water-based cooling may be limited by water availability and long-term sustainability. These considerations highlight that PV cooling must be evaluated at the system level by balancing thermal effectiveness with resource footprint, reliability, and maintainability under practical constraints.

## Interpretation and usage of the proposed selection framework

To translate the above taxonomy and unified metrics into actionable engineering guidance, the proposed cooling strategy selection framework in Figure 1 is designed as a decision-oriented pathway that links boundary conditions, engineering constraints, and objective functions to the selection of appropriate PV cooling architectures. Rather than ranking cooling methods solely by their maximum temperature reduction, the framework emphasizes scenario-dependent feasibility and system-level trade-offs, enabling cooling strategies to be screened and compared under real deployment conditions.

Specifically, the framework takes climate and application factors (e.g., ambient temperature, irradiance, wind and humidity conditions, soiling tendency, and PV installation type) as primary inputs, while simultaneously incorporating practical constraints such as water availability, allowable auxiliary power, and maintenance accessibility. Based on the targeted objectives,

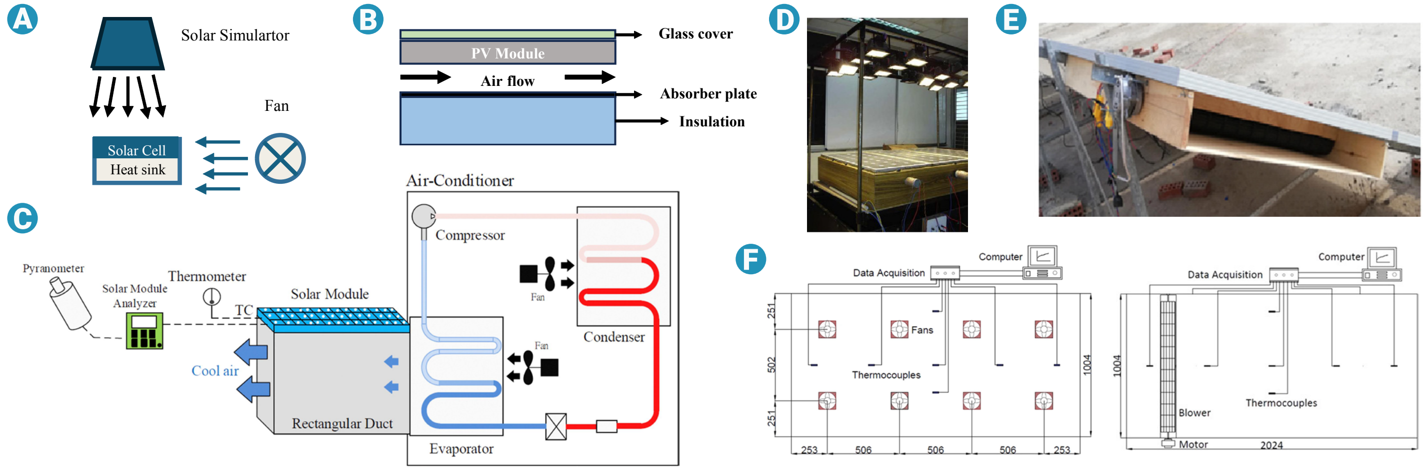



**Figure 3. Forced air cooling configurations and system-level design trade-offs** (A) Schematic illustration of basic air convection cooling configuration (front view).[50] (B) Schematic illustration of air convection cooling configuration (side view).[52] (C) Forced air cooling system employing mechanically actuated air distributors to enhance airflow uniformity.[53] (D) Experimental setup of series-connected PV modules integrated with a wooden air duct for forced air convection.[54] (E) Physical configuration of a PV panel equipped with a rear air duct and distributed fan cooling system.[55] (F) Comparative layouts of centralized blower-assisted duct cooling and back-distributed fan cooling.[55]

such as maximizing temperature suppression, maximizing net energy gain, minimizing water footprint, or improving long-term reliability, the framework guides the selection among passive, active, and hybrid cooling pathways. The final decision is then evaluated using the unified metrics summarized in Table S1, including thermal effectiveness, parasitic penalties, resource footprint, and deployment readiness.

Throughout this review, Figure 1 serves as the organizing "engineering map" that connects the evidence base in Sections 3–5 to scenario-matched recommendations. Active cooling approaches are discussed in terms of cooling intensity and controllability together with parasitic power and O&M implications; passive strategies are evaluated for their low-penalty advantages and climate sensitivity; and hybrid architectures are highlighted for their multi-objective balancing potential and scalable integration opportunities. By embedding cooling technologies into a unified selection logic, this framework supports the development of deployable PV thermal management solutions and provides a practical reference for both researchers and practitioners.

## ACTIVE COOLING STRATEGIES

Active cooling strategies aim to enhance heat removal from photovoltaic modules through externally driven processes, thereby achieving stronger and more controllable temperature regulation than passive approaches. By intensifying convection or exploiting phase-change heat transfer, active cooling can effectively suppress excessive cell temperature and mitigate thermal non-uniformity under high irradiance and high ambient temperature conditions.[50] As a result, active cooling has attracted significant attention for applications where thermal stress, hot-spot risk, or performance stability is of primary concern.

However, the deployment of active cooling systems inevitably introduces additional engineering penalties, including auxiliary power consumption, increased system complexity, and higher operation and maintenance (O&M) requirements. These penalties may partially or even fully offset the electrical gains obtained from temperature reduction if not carefully controlled. Therefore, the effectiveness of active cooling cannot be evaluated solely by its cooling intensity but must be assessed from a system-level perspective that accounts for net energy gain, resource footprint, reliability, and scalability. In this section, active cooling strategies are reviewed using the unified evaluation metrics summarized in Table S1, with emphasis on their performance envelopes, parasitic losses, and deployment feasibility under practical operating conditions.

### Forced air cooling

Forced air cooling enhances convective heat transfer from PV modules by actively driving airflow across the rear surface, thereby reducing thermal boundary layer resistance and accelerating heat dissipation. Compared with passive convection, this approach offers improved controllability and a relatively simple system architecture, making it one of the most widely investigated active cooling strategies for PV applications.

In forced air cooling systems, one or multiple fans are used to generate airflow along the backside of PV modules, either through open-channel ventilation or enclosed duct configurations (Figure 3A & B).[51,52] Typical designs include rear-mounted axial fans, duct-assisted airflow channels integrated into mounting frames, and array-level ventilation schemes for utility-scale installations. The cooling effectiveness is strongly influenced by airflow velocity, channel geometry, and module spacing, as these factors determine the extent of boundary layer disruption and convective heat transfer enhancement. Compared with liquid-based systems, forced air cooling avoids direct contact with liquids and thus reduces leakage-related risks, which simplifies system integration in many cases.

Compared with natural convection, forced air cooling significantly enhances convective heat transfer by actively disturbing the thermal boundary layer on the rear surface of photovoltaic (PV) modules. Owing to its relatively low material cost, straightforward implementation, and improved controllability, forced air convection is often regarded as one of the most economical active cooling solutions for PV systems. By adjusting airflow rate and channel configuration, forced air cooling enables effective regulation of PV operating temperature under varying irradiance conditions, which is particularly beneficial for mitigating thermal accumulation during peak solar periods.

Recent studies have demonstrated that properly designed airflow pathways can achieve meaningful temperature reduction and electrical performance enhancement. Soliman et al.[52] integrated finned radiators with a forced air system and optimized fin geometry and airflow distribution, resulting in an approximately 11% reduction in PV module temperature and a 16% increase in electrical efficiency. Similarly, Sajjad et al.[53] reported a 7.2% efficiency improvement using mechanically actuated air distributors that maintained a more uniform temperature profile under partial shading conditions, as illustrated in Figure 3C. These studies indicate that, beyond average temperature reduction, forced air cooling can also improve thermal uniformity, which is critical for suppressing mismatch losses and hot-spot formation at the module level.

Forced air cooling has also been explored in energy cascade and hybrid utilization configurations. A representative case study by Solanki et al.[54] investigated a series-connected PV system integrated with a wooden air duct, as shown in Figure 3D. Using halogen lamps to simulate solar irradiance and a DC fan to regulate airflow, the study demonstrated a progressive increase in outlet air temperature with irradiance levels up to 600 W/m$^2$. Steady-state thermodynamic analysis and MATLAB simulations revealed a thermal efficiency of 42% attributed to recovered waste heat and an electrical efficiency of 8.4%, leading to an overall energy utilization efficiency of approximately 50%. Notably, the results showed that increasing airflow rates helped stabilize system performance, highlighting the role of forced convection in balancing heat dissipation and energy recovery in PV-based energy cascade systems.

Despite these advantages, the scalability of forced air cooling systems is often constrained by parasitic power consumption associated with fan operation. Hussien et al.[55] reported a temperature reduction of 9.9 °C and an electrical efficiency gain of 2.1% using distributed fan arrays (Figure 3E). However, a comparative analysis between distributed fans and centralized ducted blower systems (Figure 3F) revealed that distributed configurations achieved a higher net energy saving of 7.9%, compared with 4.2% for centralized setups. These findings emphasize that the net benefit of forced air cooling depends not only on cooling effectiveness, but also on system-level design choices that govern auxiliary power demand and airflow distribution.

From an engineering perspective, forced air cooling generally offers moderate temperature reduction, low water footprint, and manageable system complexity, making it suitable for scenarios where water-based cooling is impractical and limited auxiliary power consumption is acceptable. However, fan-induced parasitic losses, noise, dust accumulation, and maintenance requirements must be carefully considered, particularly for large-scale or long-term deployments. When evaluated using the unified metrics summarized in Table S1, forced air cooling occupies a trade-off space characterized by relatively low resource footprint and medium technology readiness, but with net performance benefits that are highly sensitive to airflow optimization and system configuration.

As summarized in Figure 3, the engineering performance of forced air cooling is governed not only by the achievable temperature reduction, but also by airflow organization, system configuration, and auxiliary power demand, indicating that optimized airflow distribution and fan deployment are essential for maximizing net energy benefits in practical PV applications.

### Liquid circulation cooling

Liquid circulation cooling systems exploit water's high specific heat capacity to absorb and transport heat from PV modules.[56] In typical configurations, liquid cooling is implemented through closed-loop systems, including backside immersion cooling, cold plates, and microchannel heat sinks, which enable efficient heat extraction from the PV rear surface while maintaining relatively stable operating temperatures.

Recent studies have demonstrated the strong cooling potential of liquid-based systems. Xie et al.[57] employed a microchannel heat sink with three-dimensional serpentine channels fabricated by additive manufacturing, as shown in Figure 4A, achieving a 23.45% reduction in PV operating temperature under concentrated photovoltaic conditions. Such microchannel designs enhance heat transfer by increasing surface area and promoting flow mixing, making liquid circulation particularly effective for high heat flux scenarios. In addition, Bahaidarah et al.[58] integrated a water-cooled PV/T system for deployment in arid climates (Figure 4B & C), reporting a 19.3% temperature reduction and an approximately 10% increase in daily energy yield. These results highlight the capability of liquid cooling not only to suppress PV temperature, but also to enable energy cascade utilization by recovering thermal energy for secondary applications.

Emerging developments in liquid cooling focus on improving heat transfer efficiency and operational intelligence. Nanofluid additives, such as graphene-enhanced coolants, have been reported to increase effective thermal conductivity by 20–30%, while advanced control strategies based on artificial intelligence are being explored to optimize flow rate and thermal response under dynamic environmental conditions. Despite these advantages, liquid circulation cooling systems are associated with several engineering challenges, including high capital cost, pumping power consumption, and reliability risks related to leakage, corrosion, and fouling, particularly in saline or humid environments. Moreover, seasonal variability in cooling demand may lead to suboptimal system utilization if liquid circulation is not properly regulated.

From an engineering evaluation perspective, liquid circulation cooling generally provides strong temperature suppression and high controllability, but at the expense of non-negligible parasitic power consumption and increased system complexity. When assessed using the unified metrics in Table S2, liquid cooling is most suitable for applications where high thermal loads justify the additional energy and maintenance costs, such as PV/T systems, concentrated PV, or hybrid energy systems. Careful design of flow configuration, pressure drop, and material compatibility is essential to ensure positive net energy gain and long-term deployment viability.

### Spray and water film cooling

Spray and water film cooling technologies combine evaporative cooling with convective heat transfer, enabling rapid and effective temperature reduction on the PV surface.[59] By intermittently or continuously applying water in the form of fine droplets or thin films, these approaches utilize the latent heat of evaporation to extract substantial thermal energy, making them among the most powerful active cooling methods reported for PV systems.

Recent studies have focused on improving water-use efficiency and system sustainability. Hadipour et al.[60] developed a pulsed spray cooling strategy with duty-cycle modulation, as illustrated in Figure 4D, achieving an 89% reduction in water consumption while maintaining a 24.1% improvement in electrical efficiency. Such intermittent operation significantly enhances the feasibility of spray cooling by reducing resource consumption without sacrificing cooling performance. In high-temperature regions, this approach can further improve economic efficiency by extending PV module lifetime and mitigating thermal degradation, making pulsed spray cooling particularly attractive for extreme climates.

Dual-surface spray configurations have demonstrated even stronger cooling potential. Nizetic et al.[61] proposed synchronized front- and rear-side irrigation of PV modules (Figure 4E), achieving an exceptional 55.6 °C temperature reduction and a 16.3% increase in power output. Although the pump power consumption accounted for approximately 10.3% of the generated electricity, the system still realized a net efficiency gain of 7.7%, illustrating the importance of evaluating spray cooling using net performance metrics rather than peak temperature reduction alone. In addition, the long-term self-cleaning effect of water spraying can reduce soiling-related losses, lower maintenance frequency, and enhance system reliability.

Water film cooling has also been applied to bifacial PV systems to simultaneously improve optical and thermal performance. Krauter et al.[62] demonstrated that hydrophobic surface coatings combined with water film cooling (Figure 4F) preserved light absorption while achieving a 22 °C temperature reduction and a 10.3% increase in electrical efficiency. In this configuration, the water film serves a dual function by reducing optical reflection and promoting evaporative heat removal. However, water quality management remains a critical issue, as scaling, microbial growth, and excessive evaporative loss—reported to exceed 30% of total water consumption in arid regions—can compromise long-term system performance.

From an engineering standpoint, spray and water film cooling offer the highest cooling intensity among active strategies but are fundamentally constrained by water footprint, pumping power, and maintenance requirements. According to the unified evaluation framework in Table S2, these methods are best suited for high-temperature environments where water resources are available and where aggressive temperature suppression yields clear benefits in energy output and module longevity. Their deployment requires careful optimization of spray timing, flow rate, and water treatment to balance cooling effectiveness with sustainability and operational robustness.

### Summary of active cooling strategies

Active cooling strategies provide effective and controllable thermal management for photovoltaic (PV) modules by intensifying convective or evaporative heat transfer, thereby enabling substantial temperature reduction under high irradiance and high ambient temperature conditions. Compared with passive approaches, active cooling generally achieves stronger suppression of average and peak cell temperatures, as well as improved thermal uniformity, which is critical for mitigating hot-spot formation and stabilizing electrical performance. However, these advantages are accompanied by additional system-level penalties, including auxiliary power consumption, increased structural complexity, and higher operation and maintenance (O&M) requirements.

Among the reviewed active cooling approaches, forced air cooling offers a balanced solution characterized by moderate temperature reduction, near-

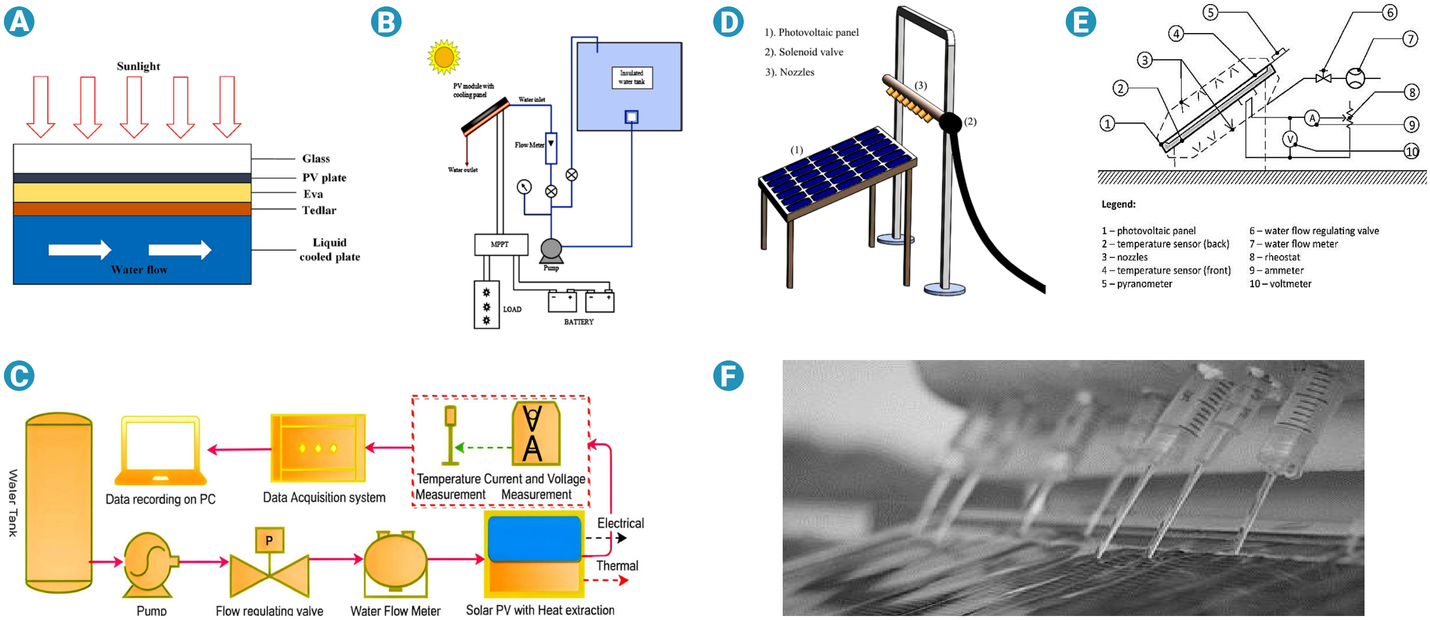



**Figure 4. Representative configurations and engineering implementations of liquid circulation cooling and spray/water film cooling strategies for PV modules** (A) Schematic illustration of a PV module with liquid cooled plate.[63] (B) Experimental schematic of a PV module employing backside liquid circulation cooling.[58] (C) Experimental test setup of a water-cooled PV/T system.[58] (D) Experimental configuration of a PV module with pulsed spray cooling.[60] (E) Experimental schematic of a PV module with dual-surface spray cooling.[61] (F) Setups of spray water film cooling applied to a PV module with hydrophobic surface treatment.[62]

zero water footprint, and relatively simple system integration. Its net performance is highly sensitive to airflow organization and fan deployment, and positive energy gains can only be ensured when parasitic power consumption is carefully constrained. Liquid circulation cooling delivers stronger and more stable thermal control by exploiting the high heat capacity of liquids and is particularly suitable for high heat-flux applications such as concentrated PV and PV/T systems. Nevertheless, pumping power demand, higher capital expenditure, and long-term reliability risks associated with leakage, corrosion, and fouling must be explicitly considered to ensure deployable net benefits. Spray and water film cooling exhibit the highest cooling intensity among active strategies, achieving exceptional temperature reduction and additional benefits such as self-cleaning and optical enhancement. Their applicability, however, is fundamentally limited by water footprint, pumping energy, and maintenance requirements, especially in water-scarce regions.

When evaluated using the unified system-level metrics summarized in Table S1, active cooling strategies occupy a trade-off space in which cooling effectiveness must be balanced against parasitic penalties, resource consumption, and deployment feasibility. In the context of the proposed cooling strategy selection framework (Figure 1), active cooling is most appropriate for scenarios where aggressive temperature suppression is required and where auxiliary energy input or water consumption can be justified by clear gains in energy yield, reliability, or system lifetime. These insights provide a quantitative and scenario-aware foundation for integrating active cooling into hybrid architectures, which are discussed in the following section.

## PASSIVE COOLING STRATEGIES

Passive cooling strategies mitigate photovoltaic (PV) temperature rise by enhancing heat dissipation or buffering thermal loads without external energy input or consumable resources during operation. Owing to their zero parasitic power consumption, low operation and maintenance (O&M) requirements, and high intrinsic reliability, passive approaches are well suited for long-term PV deployment scenarios where system simplicity, durability, and sustainability are prioritized. In contrast to active cooling, passive methods rely on favorable heat transfer pathways and environmental driving forces rather than externally imposed control, and therefore typically deliver moderate but robust thermal regulation.

From an engineering perspective, passive PV cooling can be broadly categorized according to its dominant physical mechanisms. These include natural convection–enhanced structures that strengthen buoyancy-driven airflow through geometric or mounting modifications, latent-heat-based thermal buffering using phase change materials to suppress temperature peaks, phase-change-assisted heat transport via passive heat pipes that enable directional heat removal, and environment-driven cooling mechanisms such as radiative, sorption-based, or evaporation-assisted cooling that exploit ambient thermodynamic potentials. While these approaches avoid parasitic energy penalties, their cooling effectiveness is inherently sensitive to climate conditions, installation layout, and temporal variation in thermal load.

### Natural convection-enhanced passive cooling

Natural convection–enhanced passive cooling mitigates photovoltaic (PV) temperature rise by strengthening buoyancy-driven airflow and coupled radiative heat dissipation through structural and geometric optimization, without external energy input. By exploiting temperature-induced density gradients in the surrounding air, these approaches enable continuous heat removal from the rear surface of PV modules while avoiding the parasitic power consumption and system complexity associated with active cooling. Owing to their simplicity, robustness, and sustainability, natural convection–based solutions constitute a foundational pathway for passive PV thermal management.

In natural convection cooling, heat generated within PV modules warms the adjacent air, inducing upward buoyancy flow along the module's rear surface. Structural interventions, such as vortex generators (VGs), discontinuous finned heat sinks, optimized mounting brackets, and chimney-assisted airflow channels, are employed to intensify this buoyancy-driven motion and disrupt thermal boundary layers. These designs promote enhanced convective heat exchange between the PV surface and ambient air, often accompanied by radiative heat loss from exposed surfaces.[64] Because the airflow is self-sustained by temperature differences and gravity, the cooling process operates autonomously without auxiliary energy input.

Experimental and numerical studies reported in the literature demonstrate that natural convection–enhanced cooling can achieve moderate but meaningful temperature reduction, typically within the range of 3–10 °C, depending on structural design and environmental conditions. Zhou et al.[65] showed that rectangular wing-shaped vortex generators reduced PV operating temperature by 2–3 °C under unobstructed natural convection, while aluminum-based designs provided an additional 1 °C advantage over poly-

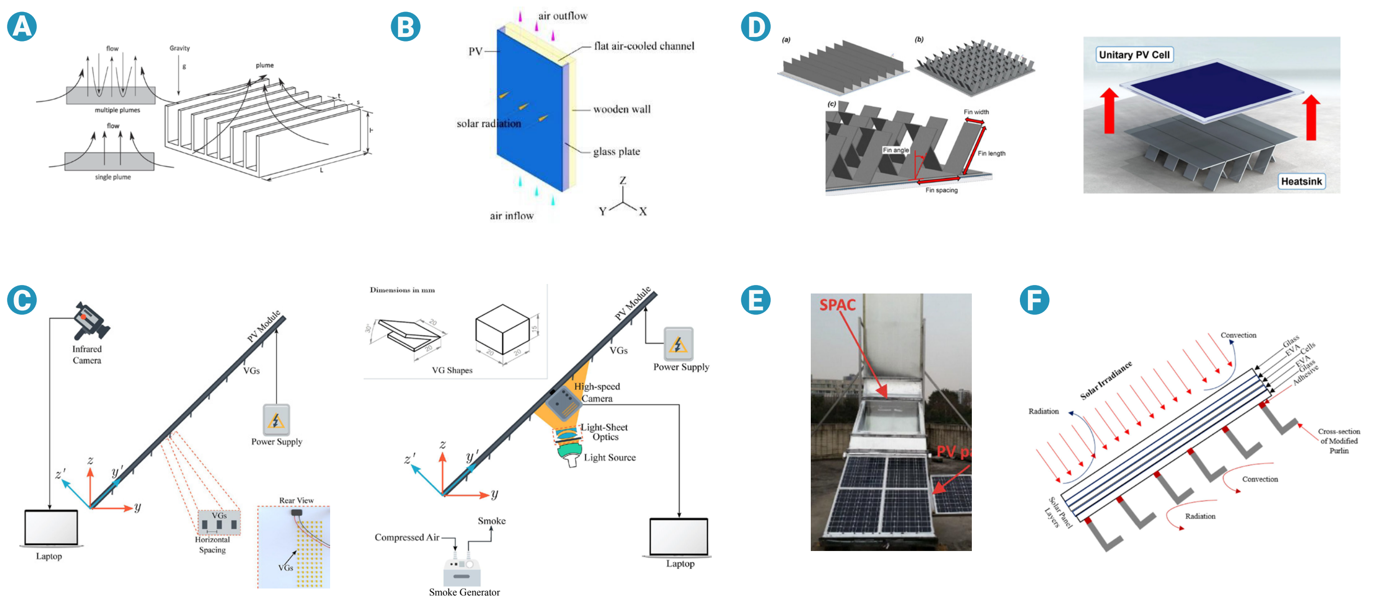



**Figure 5. Natural convection–enhanced passive cooling: structural design strategies** (A) Schematic illustration of a baseline natural air convection cooling configuration.[70] (B) Conceptual diagram of airflow organization in naturally ventilated PV mounting structures.[71] (C) Natural convection cooling enhanced by vortex generators or finned structures.[65] (D) Representative finned heat sink configurations for passive PV cooling: discontinuous fin[66] and sectional aluminum fin.[67] (E) Chimney-assisted passive airflow channel system (PACS) for PV modules.[68] (F) Structural bracket optimization using L-shaped aluminum crossbeams integrated as dual-function mounting and heat dissipation elements.[69]

mer counterparts due to improved thermal conductivity (Figure 5C & D). Hernandez-Perez et al.[66,67] reported average temperature reductions of 5.14 °C using discontinuous finned heat sinks, with localized cooling exceeding 7.28 °C under orthogonal wind conditions, and peak reductions approaching 10 °C under high irradiance (~970 W/m$^2$). Similarly, chimney-assisted passive airflow channel systems (PACS) developed by Zou et al.[68] achieved temperature drops of 10–15 °C in favorable orientations (Figure 5E), demonstrating cooling capacities comparable to low-intensity active systems.

Beyond dedicated heat sinks, structural bracket optimization provides an additional passive cooling pathway by integrating heat dissipation functionality into PV mounting systems. Al-Amri et al.[69] redesigned conventional PV support brackets as dual-function thermal dissipaters using L-shaped aluminum crossbeams, as illustrated in Figure 5F. By enhancing thermal contact between the module and bracket through conductive adhesives and applying high-emissivity surface coatings (ε ≈ 0.85), the modified structure promoted both convective and radiative heat loss. Field tests under Saudi Arabian climatic conditions demonstrated not only effective temperature reduction but also a 5 % decrease in levelized cost of energy (LCOE) over a 25-year system lifetime, highlighting the techno-economic relevance of structural integration.

A defining advantage of natural convection–enhanced cooling is the absence of parasitic power consumption, resulting in an effectively zero parasitic power ratio ($\varnothing_p$=0). Consequently, any electrical efficiency improvement achieved through temperature reduction directly translates into net energy gain. For example, optimized fin, bracket, and mounting designs have been reported to increase PV conversion efficiency by up to 4 %, while structural integration approaches further improve economic performance by reducing LCOE without introducing auxiliary energy demand.[67-69] This intrinsic net benefit makes natural convection cooling particularly attractive for decentralized PV systems and cost-sensitive large-scale deployments.

Natural convection–based cooling exhibits excellent long-term reliability due to the absence of moving parts, fluid circulation, or active control components. Structural elements such as fins, brackets, and airflow channels are generally durable and require minimal maintenance, resulting in low O&M burden over the PV system lifetime. Potential performance degradation is mainly associated with dust accumulation, partial airflow blockage, or suboptimal installation geometry. Compared with active cooling strategies, failure modes are gradual rather than abrupt, significantly reducing operational risk.

Natural convection–enhanced passive cooling is best suited for PV applications where zero auxiliary energy consumption, low maintenance, and long-term robustness are prioritized. Typical deployment scenarios include rooftop PV systems with sufficient rear ventilation, building-integrated PV installations designed with ventilated cavities, and utility-scale PV arrays employing elevated mounting structures or thermally functional brackets. However, performance remains sensitive to ambient airflow and installation orientation, and cooling effectiveness may diminish in enclosed or stagnant environments. From an engineering perspective, natural convection cooling should be regarded as a baseline passive strategy, offering stable and cost-effective thermal mitigation that can be further complemented by active or hybrid cooling approaches when stronger or more controllable temperature regulation is required.

## Latent heat and phase-change-based passive cooling

Phase-change-based passive cooling strategies mitigate photovoltaic (PV) temperature rise by exploiting latent heat effects during material phase transitions or evaporation processes, thereby enabling substantial thermal buffering and heat dissipation without external energy input. Unlike convection-dominated passive approaches, these strategies regulate PV temperature primarily through energy absorption during phase transitions, making them particularly effective under intermittent or peak thermal loads. Representative implementations include phase change material (PCM) cooling, heat pipe–assisted heat transport, and water evaporation–driven cooling systems.

***PCM-based thermal buffering.*** Phase change materials (PCMs) regulate PV temperature by absorbing excess heat during solid–liquid transitions and releasing it during cooler periods, thereby suppressing temperature peaks and reducing thermal cycling stress on PV cells.[72-76] Early experimental studies verified the feasibility of PCM cooling but also revealed its sensitivity to material selection. Wei et al.[77] integrated tea wax (melting point: 48–50 °C) into a 60 W monocrystalline PV module and achieved only a 1–2 °C temperature reduction, with negligible efficiency improvement. This limited performance highlighted the importance of matching PCM phase transition temperature with the PV operating temperature range to fully exploit latent heat capacity.

Subsequent research shifted toward simulation-assisted optimization and structural enhancement. Biwole et al.[78] employed CFD modeling to investigate the placement of paraffin RT25 on the PV backsheet under 1000 W m$^{-2}$ irradiance (Figure 6B), demonstrating stabilized module temperatures below 40 °C and effective suppression of thermal runaway. Jungwoo Park et al.[76] further combined experiments and numerical modeling by embedding paraf-

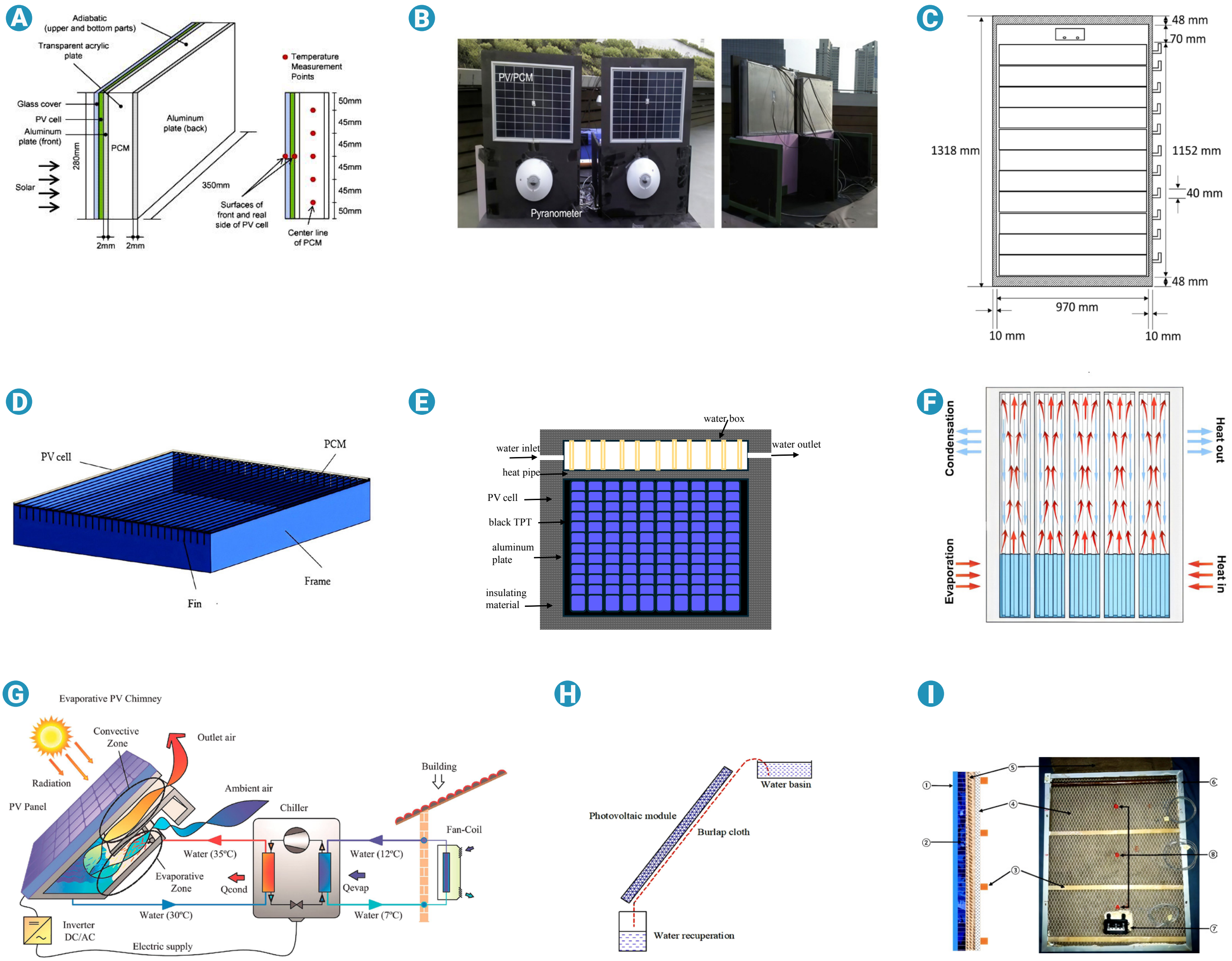



**Figure 6. Phase-change-based passive cooling strategies for PV modules** (A) Schematic diagram of a PV/PCM module.[76] (B) Experimental configuration of a PV module integrated with backsheet PCM.[78] (C) PCM encapsulated in aluminum containers to enhance heat conduction and structural stability.[80] (D) PCM structures combined with fin arrays to increase effective heat transfer area and accelerate heat dissipation during phase transition.[81] (E) Schematic diagram of a heat pipe–integrated PV/T solar collector.[84] (F) Micro heat pipe array configuration for directional heat removal from PV modules.[85] (G) Photovoltaic evaporative chimney combining buoyancy-driven airflow and evaporation-assisted cooling for enhanced passive heat dissipation.[88] (H) Gravity-fed textile-based evaporative cooling system employing capillary action to deliver water to the PV backsheet for continuous evaporation.[89] (I) Cross-sectional and rear-view schematics of capillary-driven evaporative cooling structures.[90]

fin-hydrocarbon PCM (melting point: 298 K) between aluminum heat spreaders (Figure 6A), achieving a 3.3 K temperature reduction and 3.1% efficiency gain. Their work identified critical design parameters, including PCM thickness (optimal range: 50–70 mm), orientation-dependent melting point selection, and enhanced cyclic stability through multi-layer heat transfer modeling.

Climatic adaptability has emerged as a decisive factor in PCM performance. Khan et al.[79] compared PCM cooling across different climate zones and reported a 21 °C peak temperature reduction and 13% efficiency improvement in tropical Pakistan, while efficiency gains in temperate Ireland were limited to 5.1%. Compared with temperate-climate studies in South Korea,[76] the tropical deployment exhibited 2–3 times higher efficiency gains, confirming that high ambient temperatures amplify PCM effectiveness. Structural innovations further enhanced practicality: Preeti et al.[80] integrated $CaCl_2 \cdot 6H_2O$ PCM within aluminum containers (Figure 6C), achieving 18 °C temperature reduction and 10–18% efficiency gains, while Wang et al.[81] demonstrated that finned PCM structures (Figure 6D) optimized heat dissipation by up to 31.9 °C relative to natural convection alone.

***Heat pipe-assisted passive heat transport.*** Heat pipes provide a highly efficient passive cooling pathway by transferring heat through an internal evaporation–condensation cycle, enabling directional and rapid heat removal without auxiliary power.[82] When integrated with PV modules, heat pipes reduce temperature gradients and maintain stable operating conditions by transporting heat from the evaporator region near the PV backsheet to remote condenser surfaces.

Experimental and numerical studies have demonstrated the robustness of heat pipe cooling. Wu et al.[83] integrated heat pipes into a PV/T hybrid system and achieved thermal, electrical, and overall energy efficiencies of 63.60%, 8.45%, and 10.26%, respectively, illustrating the dual function of heat pipes as both cooling elements and thermal energy harvesters. Gang et al.[84] developed a climate-resolved simulation model for heat pipe–PV/T systems (Figure 6E), showing consistent temperature regulation across diverse climates including Hong Kong, Lhasa, and Beijing. Long-term field validation by Hou et al.[85] further confirmed the reliability of micro heat pipe–supported PV/T collectors (Figure 6F), which achieved annual thermal efficiencies of 30–50% and sustained performance under variable environmental conditions.

***Evaporation-driven passive cooling.*** Evaporation-based cooling leverages the high latent heat of vaporization of water to passively dissipate heat from PV modules without external energy input.[86] By combining capillary-driven water transport with natural convection, these systems achieve effec-

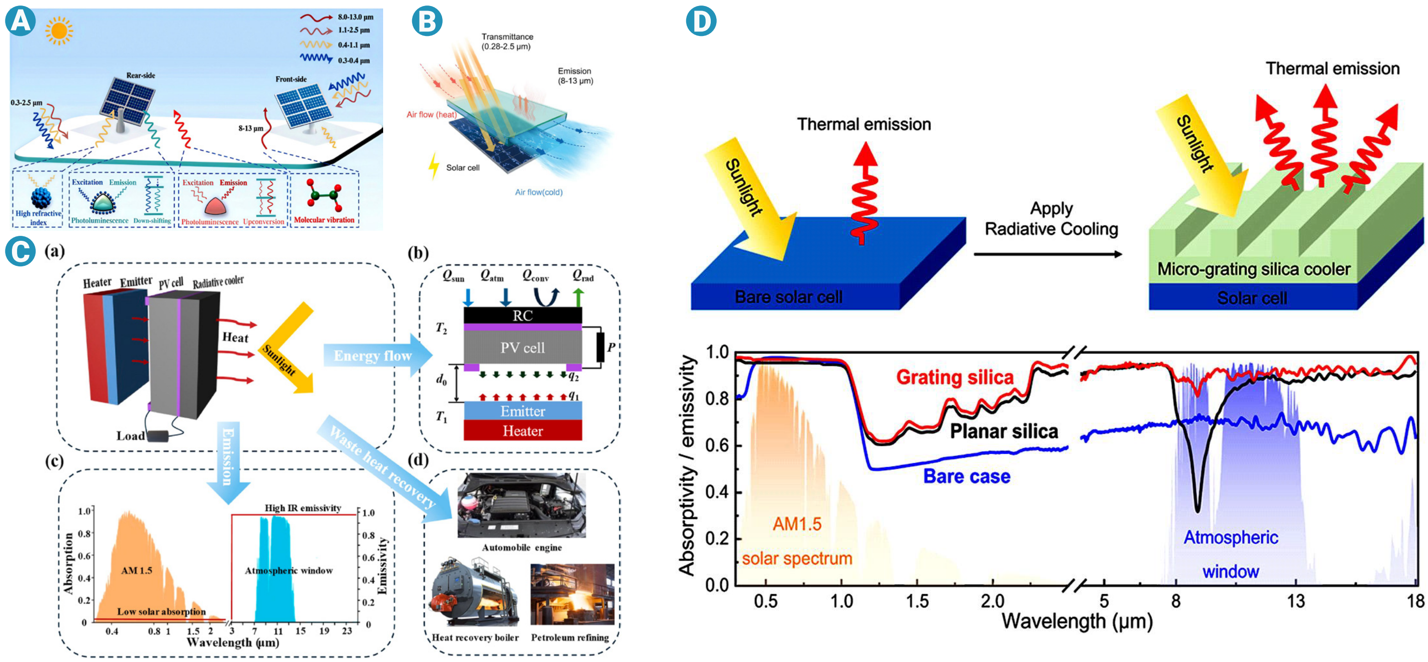



**Figure 7. Environment-driven radiative cooling strategies for PV modules** (A) Schematic of a spectrally engineered coating integrated with bifacial photovoltaic panels.[97] (B) Coordinated integration of daytime radiant cooling and solar cells.[98] (C) Near-field radiative cooling and thermophotovoltaic system using a calcite thin film.[95] (D) Cooling performance of micro-gratings for glass-encapsulated PV modules.[100]

tive temperature suppression using low-cost materials. Chandrasekar et al.[87] integrated aluminum heat spreaders with cotton core structures and achieved 5–7 °C temperature reduction and 14% efficiency gain, while reducing material cost by approximately 40% compared with PCM-based systems.

More recent studies demonstrated enhanced performance through structural integration. Lucas et al.[88] proposed a photovoltaic evaporative chimney combining evaporative and buoyancy-driven cooling (Figure 6G), achieving an 8 °C temperature drop and 7.6% peak efficiency improvement under 1000 W m$^{-2}$ irradiance. Textile-based capillary systems further improved performance: Malvika et al.[89] reported 20.2 °C temperature reduction and 18–21% efficiency gain using gravity-fed bur-cloth systems (Figure 6H), while Dida et al.[90] achieved a 20.6 °C reduction and 14.1% efficiency improvement using coarse linen materials (Figure 6I). However, evaporation-driven cooling remains highly climate-dependent and requires careful water management to mitigate evaporation loss, clogging, and maintenance challenges. Alktranee et al.[49] compared cotton core water absorption (CWWs) and rectangular aluminum fins (RAFs) in Basra, Iraq. The CWWs system reduced module temperatures by 22.3% (vs. 6.7% for RAFs) and increased power output by 73%, with a payback period of just 144 days. However, its reliance on frequent water replenishment limits applicability in arid regions. Conversely, RAFs offered lower-cost, corrosion-resistant operation with a 3.3 USD/m$^2$ material cost and a 2-year payback.

Recent advances in interfacial evaporative cooling technology further demonstrate the potential of this approach for high heat flux photovoltaic applications. Photovoltaic-solar evaporation proposed by Li et al.[91] the system covers the back of the PV module with a passive, siphony-driven water film, eliminating the need for external pumping. This study demonstrates a module level temperature reduction 22.3 °C and an improvement in absolute power conversion efficiency of 8.9%. Su et al.[92] utilized integrated photovoltaic cooling through seawater interface evaporation. The surface temperature of the photovoltaic panel could be reduced by 12 °C using alginate gel filled with uranium adsorbent, and the maximum output gain was 8%.

Despite their strong cooling potential and zero parasitic energy consumption, phase-change-based passive cooling strategies face several engineering challenges. PCM systems are limited by low thermal diffusivity in the solid phase and long-term material stability, necessitating conductive additives or structural enhancement. Heat pipes introduce fabrication complexity and material cost constraints, while evaporation-based cooling requires reliable water supply and regular maintenance. From a system-level perspective, these approaches are most effective when thermal loads are intermittent, ambient conditions are favorable, and cooling objectives prioritize peak temperature suppression over continuous regulation.

## Environment-driven passive cooling

Environment-driven passive cooling strategies regulate photovoltaic (PV) operating temperature by exploiting external environmental heat sinks or thermodynamic potentials, rather than relying on internal structural modification or stored latent heat. Typical driving forces include long-wave radiative exchange with the cold sky, moisture adsorption–desorption cycles governed by ambient humidity, and direct thermal coupling with large water bodies. These approaches are characterized by zero parasitic energy consumption and strong coupling with local climate conditions, making them highly effective in specific deployment scenarios but inherently site-dependent.

***Radiative cooling.*** Radiative cooling enables passive heat dissipation by emitting thermal radiation through the atmospheric infrared transparency window (8–13 μm), where absorption by atmospheric gases is minimal.[93-95] By spectrally separating solar absorption from mid-infrared emission, radiative cooling can suppress PV temperature rise while preserving—or even enhancing—electrical performance. Recent advances have focused on spectral engineering of coatings and emitters to overcome the inherent trade-off between solar absorption and thermal emission.[96]

Gong et al.[97] demonstrated a bifacial photovoltaic–radiative cooling (BIPV-RC) system using a spectrally selective coating (Figure 7A), achieving a 15–17.5 K temperature reduction under 1000 W m$^{-2}$ irradiance and a 23% increase in total power output compared with conventional systems. The improvement was attributed to reduced sub-bandgap heat absorption (14%) and enhanced radiative cooling power (22%). Jia et al.[98] further proposed a tandem architecture integrating radiative cooling emitters with solar cells (Figure 7B), achieving a cooling power density of 40 W m$^{-2}$ while maintaining acceptable photovoltaic efficiency (11.42%). Near-field radiative cooling concepts pushed performance limits even further: Li et al.[95] predicted a 109.3% increase in power density and a 13.6% efficiency improvement by exploiting nanoscale electromagnetic coupling (Figure 7C), highlighting radiative cooling's potential for high-temperature PV applications.

Practical constraints remain significant. Zhao et al.[99,100] showed that for

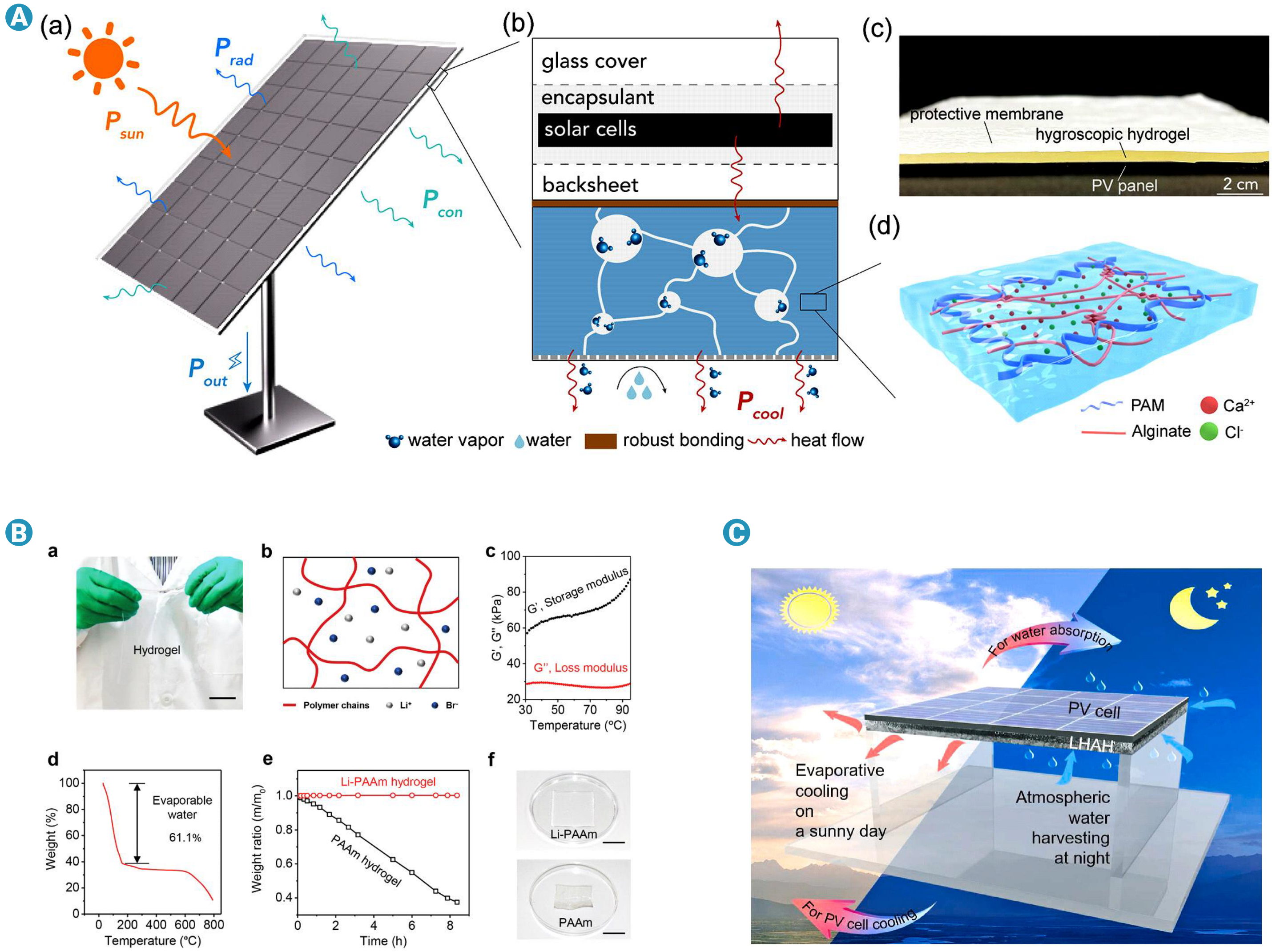



**Figure 8. Sorption-based passive cooling strategies for PV modules** (A) Moisture-absorbing composite backsheet used for passive cooling of PV panels.[102] (B) Structure and Properties of lithium-bromide-enriched polyacrylamide hydrogel.[103] (C) Photovoltaic cooling configuration based on lithium-based water-absorbing hydrogel.[104]

glass-encapsulated PV modules, most radiative coatings deliver limited cooling (<2 °C) under real atmospheric conditions, although micro-grating designs achieved a 3.6 °C reduction and 0.79% efficiency gain in space-like environments (Figure 7D). In contrast, Tang et al.[101] demonstrated that nanoporous anodized aluminum oxide films with near-blackbody emissivity (≈0.97) achieved a 7.5 K temperature reduction and 2.72% efficiency improvement under 850 W $m^{-2}$ irradiance, offering a scalable and cost-effective alternative. Overall, radiative cooling is most effective in dry, clear-sky environments, building-integrated PV systems, and extraterrestrial or high-altitude applications where atmospheric interference is minimal.

***Sorption cooling.*** Sorption cooling utilizes humidity-driven adsorption–desorption or absorption–regeneration processes to reject heat from PV modules without external energy input. By coupling thermal regulation with moisture exchange, sorption-based systems are particularly attractive in humid or water-scarce regions where conventional cooling approaches face limitations.

Li et al.[102] introduced a moisture-absorbing composite backsheet composed of polyamide/calcium alginate hydrogel and a PTFE protective membrane (Figure 8A), achieving 1.5–6.4 °C temperature reduction and 0.57–2.43% efficiency gain under Shanghai's subtropical climate. Advanced hydrogel formulations further enhanced performance: Pu et al.[103] reported that a lithium-bromide-enriched polyacrylamide hydrogel (Figure 8B) cooled PV cells by 17 °C and increased efficiency from 14.5% to 15.5% under high humidity conditions, with reversible regeneration within 15 h. Lithium-based composite hydrogels incorporating carbon nanoparticles and LiCl (Figure 8C) achieved even stronger cooling—up to 26 °C temperature reduction and 17% power enhancement—with payback periods below five years in low-latitude regions.[104] More recently, Li et al.[105] demonstrated a bio-inspired sorption cooling system that leverages a thermohaline circulation effect, achieving a record passive temperature reduction of 18.2 °C under one-sun illumination.

Despite their effectiveness, sorption-based systems are constrained by humidity dependence, material durability, and corrosion risks, particularly for salt-based adsorbents. Simplified hydrogel designs using sodium polyacrylate and LiCl demonstrated promising scalability, reducing PV temperatures by 14.1 °C and increasing efficiency by 10.2% in extreme climates while maintaining ultra-low material costs (<1 USD $m^{-2}$).[106] From an engineering perspective, sorption cooling is best suited for humid or arid–humid transitional regions, decentralized PV systems, and applications prioritizing material simplicity and low energy footprint.

***Floating and submerged cooling.*** Floating and submerged cooling strategies exploit direct thermal coupling between PV modules and large liquid reservoirs, leveraging the high thermal conductivity and heat capacity of water or dielectric liquids to suppress module temperature[51] Immersion cooling using dielectric fluids demonstrated excellent thermal control: Sun et al.[107] maintained PV cell temperatures within 20–31 °C at 910 W $m^{-2}$ DNI using silicone oil immersion (Figure 9A), while Zhu et al.[108] cooled CPV modules to 45 °C using deionized water, albeit with long-term electrical degradation concerns.

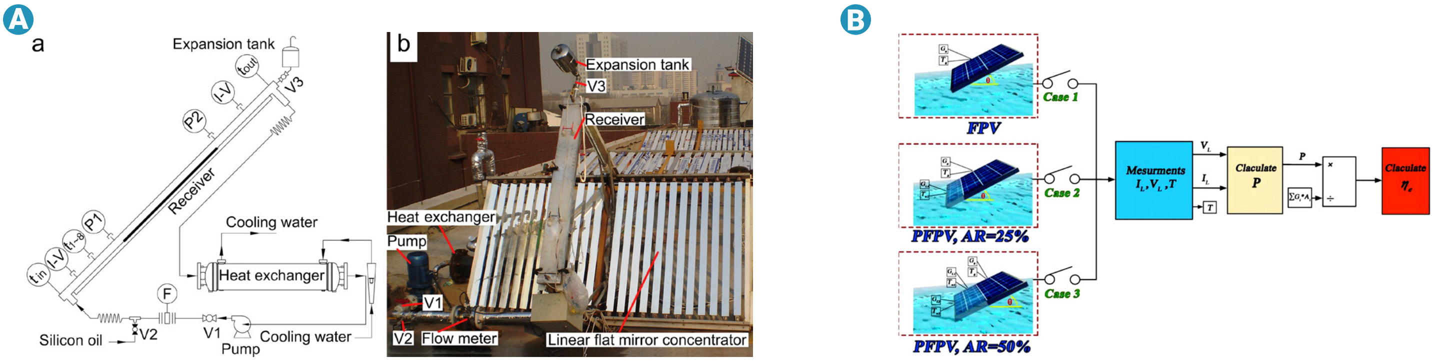



**Figure 9. Floating and submerged passive cooling strategies for PV modules (A) Schematic diagram of an immersion cooling system.[107] (B) Schematic diagram of a partial immersion cooling system.[109]**

Partial immersion approaches balance cooling effectiveness and optical losses. Elminshawy et al.[109] showed that 25% immersion reduced module temperature by 9.34 °C and increased efficiency by 3.95%, whereas higher immersion ratios led to efficiency penalties due to radiation attenuation (Figure 9B). Floating photovoltaic (FPV) systems further capitalize on enhanced airflow and evaporation over water surfaces. Field studies by Dorenkamper et al.[110] reported 14.5 °C temperature reduction and up to 6% annual power gain in tropical climates, driven by elevated convective heat transfer coefficients (~55 W $m^{-2}$ $K^{-1}$).

Although floating and submerged cooling offer strong and uniform thermal regulation, their deployment is limited by sealing complexity, material compatibility, biofouling, and site availability. From a system-level standpoint, these approaches are most suitable for water-rich regions, reservoirs, and tropical climates, where environmental conditions amplify cooling benefits and justify additional structural complexity.

## Summary of passive cooling strategies

Passive cooling strategies provide a low-penalty pathway for mitigating photovoltaic (PV) temperature rise by exploiting structural design, latent heat effects, and environmental driving forces without external energy input. Compared with active cooling, passive approaches typically deliver moderate but robust temperature regulation, characterized by zero parasitic power consumption, minimal operation and maintenance (O&M) requirements, and high long-term reliability. These attributes make passive cooling particularly attractive for large-scale, decentralized, or long-lifetime PV deployments where system simplicity and sustainability outweigh the need for aggressive temperature suppression.

Among the reviewed passive cooling mechanisms, natural convection–enhanced structures offer baseline thermal mitigation through buoyancy-driven airflow and geometric optimization, providing stable temperature reduction with negligible cost and complexity penalties. Phase-change-based strategies, including PCM thermal buffering, heat pipe–assisted heat transport, and evaporation-driven cooling, achieve stronger peak temperature suppression by leveraging latent heat effects, but their effectiveness is closely tied to climate conditions, material selection, and thermal load intermittency. Environment-driven cooling approaches, such as radiative cooling, sorption-based cooling, and floating or submerged PV systems, directly utilize external heat sinks (sky, humidity gradients, or water bodies), enabling notable cooling performance under favorable conditions while introducing pronounced site dependence.

When evaluated using the unified system-level metrics summarized in Table S1, passive cooling strategies occupy a complementary design space relative to active approaches. Rather than maximizing instantaneous temperature reduction, passive cooling prioritizes net energy gain, durability, and deployment feasibility, making climate-aware selection and integration essential. Within the proposed cooling strategy selection framework (Figure 1), passive cooling serves as either a standalone solution for low-penalty thermal management or a foundational layer that can be synergistically combined with active methods in hybrid architectures to balance performance, cost, and reliability. The summarized engineering-oriented comparison of representative passive cooling strategies for photovoltaic systems is presented in Table S3.

# HYBRID COOLING STRATEGIES

Hybrid cooling strategies transcend single-mode passive or active approaches by synergistically integrating complementary heat dissipation mechanisms, thereby overcoming inherent limitations such as climate sensitivity, limited cooling intensity, or parasitic energy penalties. By combining passive cooling elements (e.g., phase change materials, radiative cooling, sorption processes) with adaptive structures or auxiliary energy conversion components, hybrid systems aim to achieve enhanced thermal regulation, improved climate adaptability, and net energy benefits under complex and variable operating conditions.

From an engineering perspective, hybrid cooling is not simply a superposition of multiple techniques, but a coordinated design philosophy in which different mechanisms operate over distinct time scales, temperature ranges, or environmental conditions. This "1 + 1 > 2" effect enables hybrid systems to maintain stable PV temperatures across diurnal cycles, seasonal variations, and extreme climates, making them particularly attractive for urban-integrated photovoltaics, desert deployments, and high-performance PV applications. It should be noted that while some hybrid architectures incorporate thermoelectric generators (TEGs) to harvest waste heat, their primary function is energy cascading rather than direct cell temperature suppression. This review distinguishes between multi-mechanism thermal management (aimed solely at reducing $T_{cell}$) and cooling-plus-harvesting integration (which utilizes the removed heat).

## Adaptive hybrid systems coupling evaporation and environmental sensing

One representative hybrid strategy integrates evaporation-driven cooling with adaptive control, enabling passive mechanisms to operate efficiently under changing environmental conditions. Li et al.[111] proposed a photovoltaic system with a self-adaptive wicking evaporator (PV-SWE), as shown in Figure 10A, in which a thin-film evaporator forms a controlled water film on the PV backsheet through capillary siphoning. Evaporative cooling is activated only when thermal demand and water availability are favorable, minimizing unnecessary resource consumption.

The system employs a tri-modal control strategy based on solar irradiance, module temperature, and water level, allowing seamless switching between passive evaporation, standby operation, and regeneration modes. Compared with standalone PCM or continuously operating evaporative cooling, PV-SWE reduced water consumption by 40% and operational costs by 30%, while long-term net present value analysis confirmed its economic viability for large-scale deployment. This work highlights the importance of adaptive hybridization, where passive cooling is selectively activated rather than continuously imposed.

## Thermochemical and adsorption–reaction hybrid cooling

Hybrid cooling can also be achieved by coupling multiple thermodynamic processes to enhance heat absorption density and extend cooling duration.

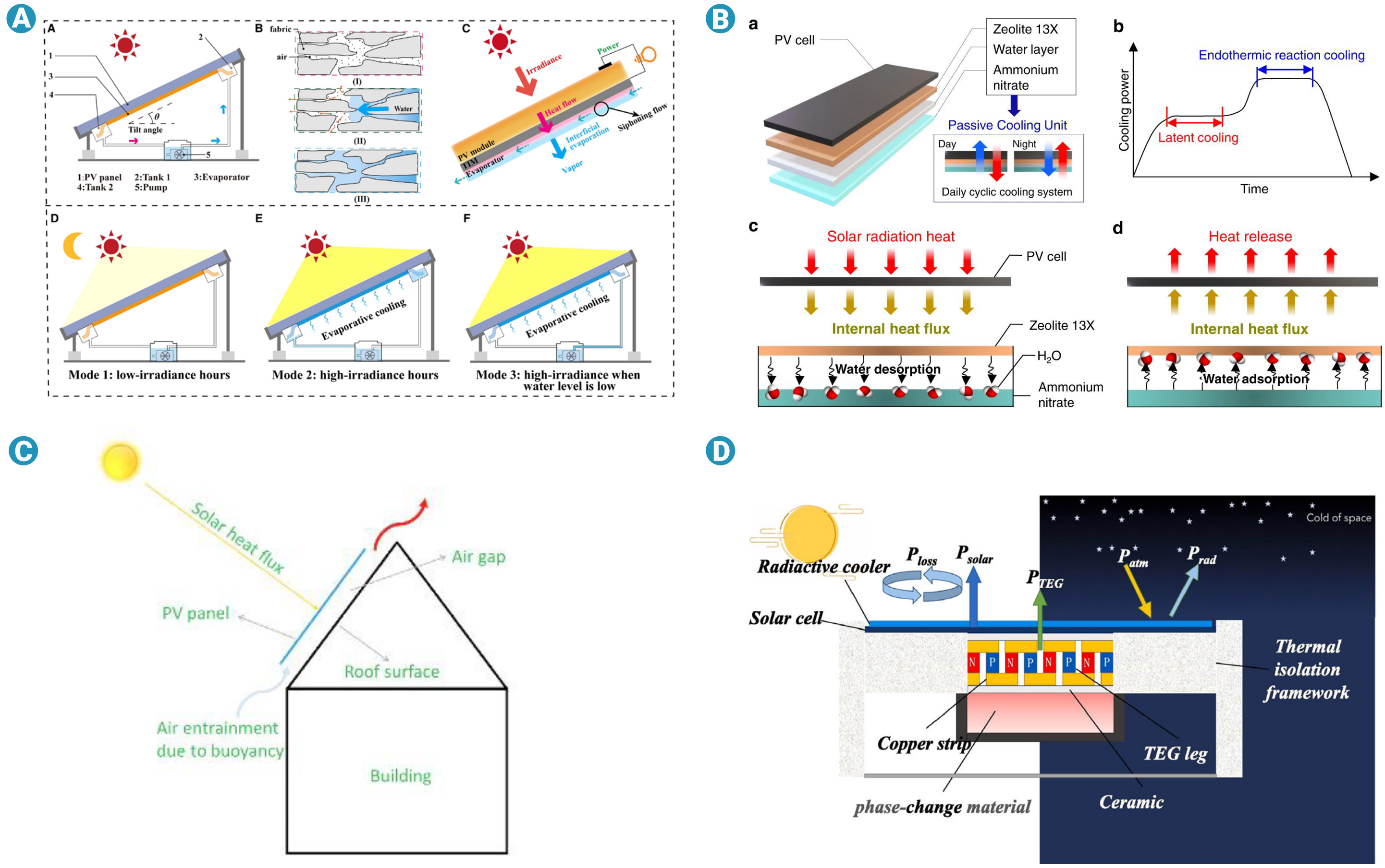



**Figure 10. Representative hybrid cooling strategies for PV modules** (A) Self-adaptive photovoltaic system with a wicking evaporator (PV-SWE).[111] (B) Adsorption–reaction hybrid cooling cycle coupling zeolite-based moisture sorption with endothermic chemical reactions.[112] (C) Building-integrated photovoltaic (BIPV) ventilation system combining radiative cooling and buoyancy-driven natural convection.[113] (D) Multifunctional hybrid module integrating radiative cooling, phase change materials (PCM), and thermoelectric generators (TEG).[114]

Kim et al.[112] developed an adsorption–reaction cooling system that exploits the inverse relationship between water adsorption and temperature in 13X zeolite, combined with the endothermic dissolution of ammonium nitrate, as illustrated in Figure 10B. During daytime operation, solar heat drives water desorption from the zeolite, while nighttime cooling enables reverse adsorption and chemical regeneration.

This coupled adsorption–reaction cycle achieved a 14.9 °C temperature reduction and 10% efficiency improvement in crystalline silicon PV cells. Notably, the effective heat flux density reached 1923 W $m^{-2}$, exceeding conventional PCM-based cooling by nearly threefold. The system demonstrates how thermochemical hybridization can significantly intensify passive cooling performance, albeit at the cost of increased material complexity and system integration challenges.

## Hybrid cooling integrated with building and energy systems

Hybrid cooling strategies are particularly attractive in building-integrated photovoltaic (BIPV) applications, where thermal management can be co-optimized with architectural and urban energy performance. Ahmadi et al.[113]proposed a BIPV ventilation system combining radiative cooling and buoyancy-driven natural ventilation, as shown in Figure 10C. By optimizing roof emissivity and airflow pathways through three-dimensional CFD simulations, the system enhanced convective heat removal while reducing thermal stress on PV modules.

Under high heat flux conditions, this hybrid design achieved a 12% efficiency improvement while simultaneously contributing to building cooling and improved urban microclimate regulation. This example illustrates the value of system-level hybridization, where PV cooling performance is enhanced not only through material selection but also through integration with the surrounding built environment.

## Multi-functional hybrid systems combining cooling and energy conversion

More advanced hybrid architectures integrate thermal management with auxiliary energy harvesting, aiming to extract additional value from PV waste heat. Lv et al.[114] developed a multifunctional module combining radiative cooling, phase change materials (PCM), and thermoelectric generators (TEG), as shown in Figure 10D. The system employs PDMS/$SiO_2$ nanocomposite films to provide daytime radiative cooling (achieving 2.5–7 °C temperature reduction), while PCM layers stabilize module temperature during nighttime operation.

Coupling the thermal gradient with TEG enables ancillary electricity generation and contributes to extending PV module lifespan. Simulations predicted a 20% daytime efficiency enhancement and a projected 15-year operational durability under arid climate conditions. However, trade-offs remain between radiative film transmittance, PCM phase transition kinetics, and overall system complexity, underscoring the need for careful co-design.

## Engineering assessment and outlook

Hybrid cooling strategies offer a powerful pathway for addressing the limitations of single-mode cooling by distributing thermal regulation across multiple mechanisms, time scales, and environmental drivers. Their key advantages include enhanced climate adaptability, improved thermal stability, and the potential for multi-functional integration with energy harvesting or building systems. However, these benefits come at the expense of increased system complexity, higher initial cost, and more demanding O&M requirements.

From an engineering perspective, hybrid cooling is most suitable for extreme climates, urban-integrated PV systems, and applications where performance stability and lifetime extension justify added complexity. Future developments are expected to focus on modular hybrid designs, AI-assisted control strategies, durable multi-functional materials, and lifecycle-oriented optimization to balance performance, cost, and sustainability. Within the proposed cooling strategy selection framework (Figure 1), hybrid cooling represents the final optimization layer, enabling tailored solutions that bridge the gap between passive robustness and active controllability.

## CONCLUSIONS AND PERSPECTIVES

### Conclusions

This review systematically examined photovoltaic (PV) cooling strategies from an engineering-oriented perspective, shifting the focus from isolated performance metrics toward deployable, system-level thermal management solutions. By organizing cooling technologies into active, passive, environment-driven, and hybrid categories, and evaluating them using unified metrics, including temperature reduction, parasitic energy penalties, resource footprint, reliability, and climate dependence, this work establishes a coherent framework for cooling strategy selection across diverse application scenarios.

Active cooling strategies, such as forced air, liquid circulation, and spray-based cooling, provide strong and controllable temperature suppression, making them suitable for high-heat-flux or performance-critical applications. However, their effectiveness must be carefully balanced against auxiliary power consumption, water use, and O&M requirements to ensure positive net energy gains. Passive cooling strategies, including natural convection enhancement, phase-change-based buffering, and environment-driven mechanisms, offer low-penalty and highly reliable thermal mitigation, prioritizing long-term robustness and sustainability over maximum cooling intensity. Hybrid cooling architectures further extend the design space by synergistically combining complementary mechanisms, enabling adaptive, climate-resilient, and multi-functional thermal management under complex operating conditions.

By integrating these insights into a cooling strategy selection framework (Figure 1), this review highlights that no single cooling approach is universally optimal. Instead, effective PV thermal management requires scenario-aware decision-making that accounts for climate conditions, installation constraints, resource availability, and system objectives. In this context, cooling should be treated not as an auxiliary add-on, but as an integral component of PV system design that directly influences efficiency, reliability, and lifecycle performance.

### Engineering design perspectives

From an engineering standpoint, several key principles emerge for the future development and deployment of PV cooling technologies:

1. Climate-aware selection over universal optimization

Cooling effectiveness is fundamentally constrained by environmental driving forces. Radiative cooling excels in dry, clear-sky regions; sorption and evaporation-based cooling thrive under specific humidity conditions; floating and immersion cooling benefit water-rich environments. Future designs should prioritize climate-matched solutions rather than pursuing universal peak performance.

2. Net energy and lifecycle performance as primary metrics

Maximum temperature reduction alone is insufficient for engineering evaluation. Parasitic power consumption, material durability, maintenance burden, and lifecycle economics must be incorporated into decision-making to ensure long-term net benefits.

3. Structural and system-level integration

Cooling performance can be significantly enhanced by embedding thermal management functions into PV mounting structures, building envelopes, and energy systems. Such integration reduces system complexity and unlocks additional benefits, including building cooling, waste heat recovery, and urban microclimate regulation.

4. Hybridization as a targeted optimization layer

Hybrid cooling strategies should be deployed selectively to address specific limitations of single-mode systems, rather than indiscriminately combining multiple techniques. Adaptive control, thermochemical coupling, and multi-functional materials represent promising pathways for achieving "1 + 1 > 2" performance gains when justified by application requirements. Advancements in hybridization, material science, and intelligent controls will drive the next generation of PV cooling technologies. By synergizing efficiency, sustainability, and cost-effectiveness, these innovations will ensure reliable, high-yield photovoltaic operation—even in extreme climates—accelerating global adoption of renewable energy systems.

### Future outlook

Looking ahead, the evolution of PV cooling technologies must directly confront the limitations highlighted in prior reviews, such as the long-term stability of phase-change materials, the high cost of micro/nano-fabrication for radiative emitters, and the absence of standardized lifecycle assessment methodologies. Materials innovation, digital intelligence, and system integration will increasingly shape this evolution. However, a critical engineering challenge persists for radiative cooling: to fully realize its potential in field-deployed photovoltaic modules, future advancements must mitigate the spectral mismatch induced by commercial PV glass encapsulation layers. Meanwhile, data-driven optimization—enabled by machine learning and IoT-based monitoring—will facilitate adaptive cooling strategies that respond dynamically to environmental conditions and operational demands.

At the system level, future PV installations are likely to adopt modular and hybrid thermal management architectures, enabling scalable deployment across diverse climates and application scenarios. Coupling cooling with auxiliary functions such as energy storage, thermoelectric generation, or water management will further enhance the overall value proposition of PV systems. Importantly, policy incentives and sustainability-oriented design standards may accelerate the adoption of low-penalty passive and hybrid cooling solutions, particularly in regions pursuing large-scale renewable integration.

In summary, PV cooling is transitioning from a performance-enhancement accessory to a core design dimension of next-generation photovoltaic systems. The innovation of the engineering-oriented perspective proposed in this study lies in overcoming the limitations of single temperature-reduction-based evaluation, and instead systematically assessing photovoltaic cooling technologies from multiple dimensions, including deployability, resource utilization, and reliability. By adopting the proposed unified metrics and the climate-aware strategy selection framework, future research can better navigate the trade-offs between cooling intensity and economic viability. This systematic approach is critical for extending system lifetime and supporting the global transition toward sustainable energy systems. The summary of engineering-oriented synthesis and future roadmap of photovoltaic cooling technologies is presented in Figure S2.

## REFERENCES


1. Liu J., Zhou Y., Zhou Z., et al. (2024). Passive photovoltaic cooling: Advances toward low-temperature operation. *Adv. Energy Mater.* **14**:2302662. DOI:10.1002/aenm.202302662
2. Zhou N., Price L., Dai Y.D., et al. (2019). A roadmap for China to peak carbon dioxide emissions and achieve a 20% share of non-fossil fuels in primary energy by 2030. *Appl. Energy* **239**:793–819. DOI:10.1016/j.apenergy.2019.01.154
3. Huang B., Zhou Z., Li Z., et al. (2025). Research progress on the impact of wind-sand flow on desert photovoltaic modules and their power generation efficiency. *Acta Aerodyn. Sin.* **43**:64–79. DOI:10.7638/kqdlxxb-2024.0219
4. Green M.A., Dunlop E.D., Yoshita M., et al. (2025). Solar cell efficiency tables (Version 65). *Prog. Photovolt.* **33**:3–15. DOI:10.1002/pip.3867
5. Wikoff H.M., Reese S.B. and Reese M.O. (2022). Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics. *Joule* **6**:1710–1725. DOI:10.1016/j.joule.2022.06.006
6. Li Y., Fu J., Mao X.Y., et al. (2021). Enhanced bulk photovoltaic effect in two-dimensional ferroelectric CuInP2S6. *Nat. Commun.* **12**:5896. DOI:10.1038/s41467-021-26200-3
7. Dallaev R., Pisarenko T., Papez N., et al. (2023). Overview of the current state of flexible solar panels and photovoltaic materials. *Materials* **16**:5839. DOI:10.3390/ma16175839
8. Zhang Z.X., Chen M., Zhong T., et al. (2023). Carbon mitigation potential afforded by rooftop photovoltaic in China. *Nat. Commun.* **14**:2347. DOI:10.1038/s41467-023-38079-3
9. Sadrtinov K.D. and Kiseleva S.V. (2026). Prospects for the development of renewable energy in China until 2050 in the context of the climate agenda: An assessment of investment costs and their feasibility. *Clean. Energy Syst.* :100241. DOI:10.1016/j.cles.2026.100241

10. Lu F., Wang H., Guo Y., et al. (2019). Research on the performance of solar photovoltaic system based on buried pipe assisted cooling. *Acta Energiae Solaris Sin.* 40:1626–1631. DOI:10.19912/j.0254-0096.2019.06.019
11. Naiara Y., Jon A., Werther C., et al. (2021). Photovoltaic modules encapsulated in composite material modified with ultraviolet additives. *Sol. Energy Mater. Sol. Cells* 230:111250. DOI:10.1016/j.solmat.2021.111250
12. He S., Miao J., Zhao B., et al. (2023). Numerical simulation of flow and heat transfer in natural ventilation cooling system of solar panels. *Proc. CSEE* 43:3811–3822. DOI:10.13334/j.0258-8013.pcsee.213093
13. Cai Y., Yang Y., Huang X., et al. (2024). Research progress of photovoltaic-phase change coupling system and its building application. *Build. Sci.* 40:116–127. DOI:10.13614/j.cnki.11-1962/tu.2024.04.13
14. Shilpa K., Aniruddha P., Ankit B., et al. (2022). Thermal management of solar panels for overall efficiency enhancement using different cooling techniques. *Int. J. Environ. Res.* 16. DOI:10.1007/s41742-022-00431-8
15. Ramkiran B., Sundarabalan C. and K.S. (2021). Sustainable passive cooling strategy for PV module: A comparative analysis. *Case Stud. Therm. Eng.* :101317. DOI:10.1016/j.csite.2021.101317
16. Zhiming X., Qinglu K., Hongwei Q., et al. (2023). Cooling characteristics of solar photovoltaic panels based on phase change materials. *Case Stud. Therm. Eng.* 41:102667. DOI:10.1016/j.csite.2022.102667
17. E.S.S., Bianca V., Naseem A., et al. (2022). Increased panel height enhances cooling for photovoltaic solar farms. *Appl. Energy* 325:119819. DOI:10.1016/j.apenergy.2022.119819
18. Salman A., Senji L., Zhenpeng L., et al. (2022). Enhanced radiative cooling of solar cells by integration with heat pipe. *Appl. Energy* 308:118363. DOI:10.1016/j.apenergy.2021.118363
19. Tian Y., Yan J., Peng Y., et al. (2022). Jet impact cooling characteristics of solar dense photovoltaic modules under high energy flow density. *Acta Energiae Solaris Sin.* 043.
20. Meiwei W., Shiyang T., Huan X., et al. (2021). Cooling performance optimization of air-cooled battery thermal management system. *Appl. Therm. Eng.* 195:117242. DOI:10.1016/j.applthermaleng.2021.117242
21. Chen H., Shao Y., Yang H., et al. (2024). Numerical study of heat pipe heat exchanger based on concentrating solar photovoltaic cell system. *Renew. Energy Resour.* 42:167–173.
22. Mechanical S.o., Manufacturing Engineering – UNSW S., Australia, Mechanical S.o., et al. (2018). Microchannel cooling of concentrator photovoltaics: A review. *Renew. Sustain. Energy Rev.* 90:1041–1059. DOI:10.1016/j.rser.2018.04.010
23. Mahmoudi S.E., Issa C., Aaron G., et al. (2021). Review of intelligent control systems for natural ventilation as passive cooling strategy for UK buildings and similar climatic conditions. *Energies* 14:4388. DOI:10.3390/en14154388
24. Royne A., Dey C.J. and Mills D.R. (2004). Cooling of photovoltaic cells under concentrated illumination: A critical review. *Sol. Energy Mater. Sol. Cells* 86:451–483. DOI:10.1016/j.solmat.2004.09.003
25. Chandrasekar M., Rajkumar S. and Valavan D. (2015). A review on the thermal regulation techniques for non integrated flat PV modules mounted on building top. *Energy Build.* 86:692–697. DOI:10.1016/j.enbuild.2014.10.071
26. Siecker J., Kusakana K. and Numbi B.P. (2017). A review of solar photovoltaic systems cooling technologies. *Renew. Sustain. Energy Rev.* 79:192–203. DOI:10.1016/j.rser.2017.05.053
27. Arash M., Mousa F., Mofid G.-B., et al. (2022). A review of passive cooling of photovoltaic devices. *Clean. Eng. Technol.* 11:100579. DOI:10.1016/j.clet.2022.100579
28. Kumar T.M., Venktesh M., Rahul D., et al. (2023). Effects of active cooling techniques to improve the overall efficiency of photovoltaic module: An updated review. *E3S Web Conf.* 387:01012. DOI:10.1051/e3sconf/202338701012
29. Li H., Zhao J., Li M., et al. (2019). Performance analysis of passive cooling for photovoltaic modules and estimation of energy-saving potential. *Sol. Energy* 181:70–82. DOI:10.1016/j.solener.2019.01.014
30. Sato D. and Yamada N. (2019). Review of photovoltaic module cooling methods and performance evaluation of the radiative cooling method. *Renew. Sustain. Energy Rev.* 104:151–166. DOI:10.1016/j.rser.2018.12.051
31. Luo X., Zhang Y., Liu L., et al. (2025). A self-powered Ag/β-Ga2O3 photodetector with broadband response from 200 to 980 nm based on the photovoltaic and pyro-phototronic effects. *J. Mater. Sci. Technol.* 206:125–134. DOI:10.1016/j.jmst.2024.04.010
32. Dong Y. (2021). Crystalline silicon solar cell conductive paste with the preparation and properties of organic carrier research. *(Taiyuan University of Science and Technology).*
33. Kemppainen E., Aschbrenner S., Bao F., et al. (2020). Effect of the ambient conditions on the operation of a large-area integrated photovoltaic-electrolyser. *Sustain. Energy Fuels* 4:4831–4847. DOI:10.1039/D0SE00921K
34. Kurniawati I. and Sung Y. (2024). A review of heat dissipation and absorption technologies for enhancing performance in photovoltaic–thermal systems. *Energies* 17:1721. DOI:10.3390/en17071721
35. K.M.T. and Adil H.A. (2022). Optimization the performance of photovoltaic panels using aluminum-oxide nanofluid as cooling fluid at different concentrations and one-pass flow system. *Results Eng.* 15:100541. DOI:10.1016/j.rineng.2022.100541
36. Karavioti A., Duros V. and Stathatos E. (2024). Transparent luminescent down-conversion coating for improved performance and enhanced stability of carbon-based perovskite solar cells. *Opt. Mater.* 154:115757. DOI:10.1016/j.optmat.2024.115757
37. Chen Y.T., Xia W.X., Zhou Y., et al. (2025). Efficient photothermal conversion and Z-scheme charge transfer in narrow-gap semiconductor heterojunction for photothermal-assisted photocatalysis. *J. Environ. Chem. Eng.* 13:115147. DOI:10.1016/j.jece.2024.115147
38. Yakubu S., Samikannu R., Gawusu S., et al. (2025). A holistic review of the effects of dust buildup on solar photovoltaic panel efficiency. *Sol. Compass* 13:100101. DOI:10.1016/j.solcom.2024.100101
39. Liu Z., Gong Y., Wang Z., et al. (2024). Revealing the intrinsic mechanisms of hot and cold spots within a locally shaded photovoltaic module based on micro-electrical characteristics. *Energies* 17:4462. DOI:10.3390/en17174462
40. Ai Z., Ma T., Zhang Y., et al. (2024). Unveiling energy conversion mechanisms and regulation strategies in perovskite solar cells. *Small* 20:e2404012. DOI:10.1002/smll.202404012
41. Wei J., Chen H., Liu J., et al. (2025). Radiative cooling technologies toward enhanced energy efficiency of solar cells: Materials, systems, and perspectives. *Nano Energy* 136:110680. DOI:10.1016/j.nanoen.2025.110680
42. Ngoc T.N., Sanseverino E.R., Quang N.N., et al. (2019). A hierarchical architecture for increasing efficiency of large photovoltaic plants under non-homogeneous solar irradiation. *Sol. Energy* 188:1306–1319. DOI:10.1016/j.solener.2019.07.033
43. Baqiya M.A., Purwandari E., Asih R., et al. (2025). A brief review and prospect of amorphous carbon and reduced graphene oxides derived from biomass as a low cost and new photovoltaic cell. *Appl. Surf. Sci.* 700:163203. DOI:10.1016/j.apsusc.2025.163203
44. Yang L.-H., Liang J.-D., Hsu C.-Y., et al. (2019). Enhanced efficiency of photovoltaic panels by integrating a spray cooling system with shallow geothermal energy heat exchanger. *Renew. Energy* 134:970–981. DOI:10.1016/j.renene.2018.11.089
45. Wu Z., Hu Y., Wen J.X., et al. (2020). A review for solar panel fire accident prevention in large-scale PV applications. *IEEE Access* 8:132466–132480. DOI:10.1109/ACCESS.2020.3010212
46. Hao S., Wang H., Ma X., et al. (2024). Hot spot fault detection of photovoltaic modules based on high-order spatial interaction network. *Acta Energiae Solaris Sin.* 45:358–366. DOI:10.19912/j.0254-0096.tynxb.2023-0574
47. Houchmand L.J., Martí M.M. and Domingo S.G. (2024). Influence of PV panels on convective heat flux in different roofs in the Mediterranean: Effects on the urban heat island. *Build. Environ.* 266:112097. DOI:10.1016/j.buildenv.2024.112097
48. Skoplaki E. and Palyvos J. A. (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar Energy* 83:614-624. DOI:10.1016/j.solener.2008.10.008
49. Alktranee M. and Péter B. (2023). Energy and exergy analysis for photovoltaic modules cooled by evaporative cooling techniques. *Energy Reports* 9:122–132. DOI:10.1016/j.egyr.2022.11.177
50. Ding D., Ding W., Jiao J., et al. (2024). Effects of volume fraction of short-cut quartz fibers on mechanical and thermal properties of SiO2f/SiO2 composites. *J. Aust. Ceram. Soc.* 60:689–699. DOI:10.1007/s41779-024-01034-6
51. Kumar P.S., Omprakash S.P., Varun G., et al. (2022). A detailed review on the performance of photovoltaic/thermal system using various cooling methods. *Sustain. Energy Technol. Assess.* 51:101844. DOI:10.1016/j.seta.2021.101844
52. Soliman A.M.A., Hassan H. and Ookawara S. (2019). An experimental study of the performance of the solar cell with heat sink cooling system. *Energy Procedia* 162:127–135. DOI:10.1016/j.egypro.2019.04.014
53. Sajjad U., Amer M., Ali H.M., et al. (2019). Cost effective cooling of photovoltaic modules to improve efficiency. *Case Stud. Therm. Eng.* 14:100420. DOI:10.1016/j.csite.2019.100420
54. Solanki S.C., Dubey S. and Tiwari A. (2009). Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors. *Appl. Energy* 86:2421–2428. DOI:10.1016/j.apenergy.2009.03.013
55. Ahmed H., Abdelgalil E. and M.E.-B.H. (2023). Experimental and numerical investigation for PV cooling by forced convection. *Alex. Eng. J.* 64:427–440. DOI:10.1016/j.aej.2022.09.006
56. Dirawi H., Wang Q., Hu M., et al. (2024). A hydronic closed-loop photovoltaic cooling system designed for hot and arid regions: Performance evaluation and degradation rate/lifetime analysis. *Appl. Energy* 373:123999. DOI:10.1016/j.apenergy.2024.123999
57. Xie L., Li H., Zhang Y., et al. (2023). Topology optimization and numerical analysis of cold plates for concentrating photovoltaic thermal management. *Case Stud. Therm. Eng.* 52:103713. DOI:10.1016/j.csite.2023.103713
58. Bahaidarah H., Subhan A., Gandhidasan P., et al. (2013). Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. *Energy* 59:445–453. DOI:10.1016/j.energy.2013.07.050
59. Saada S.A., Nebbali R., Kecili I., et al. (2025). Operating temperature and electrical efficiency of a photovoltaic panel cooled by laminar water film flowing on its front face: Experimental and numerical approach. *Mater. Today Sustain.* 30:101093. DOI:10.1016/j.mtsust.2025.101093

60. Hadipour A., Rajabi Zargarabadi M. and Rashidi S. (2021). An efficient pulsed-spray water cooling system for photovoltaic panels: Experimental study and cost analysis. *Renew. Energy* **164**:867–875. DOI:10.1016/j.renene.2020.09.021
61. Nižetić S., Čoko D., Yadav A., et al. (2016). Water spray cooling technique applied on a photovoltaic panel: The performance response. *Energy Convers. Manage.* **108**:287–296. DOI:10.1016/j.enconman.2015.10.079
62. Krauter S. (2004). Increased electrical yield via water flow over the front of photovoltaic panels. *Sol. Energy Mater. Sol. Cells* **82**:131–137. DOI:10.1016/j.solmat.2004.01.011
63. Liyao X., Hongmin L., Yan Z., et al. (2023). Topology optimization and numerical analysis of cold plates for concentrating photovoltaic thermal management. *Case Stu. Ther. Eng.* **52.** DOI:10.1016/j.Csite.2023.103713
64. Ismail M., Ali A.M. and Pereira S.-C.C. (2025). Vortex generators in heat sinks: Design, optimisation, applications and future trends. *Results Eng.* **25**:104216. DOI:10.1016/j.rineng.2025.104216
65. Zhou Z., Tkachenko S., Bahl P., et al. (2022). Passive PV module cooling under free convection through vortex generators. *Renew. Energy* **190**:319–329. DOI:10.1016/j.renene.2022.03.133
66. Hernandez-Perez J.G., Carrillo J.G., Bassam A., et al. (2021). Thermal performance of a discontinuous finned heatsink profile for PV passive cooling. *Appl. Therm. Eng.* **184**:116238. DOI:10.1016/j.applthermaleng.2020.116238
67. Hernandez-Perez J.G., Carrillo J.G., Bassam A., et al. (2020). A new passive PV heatsink design to reduce efficiency losses: A computational and experimental evaluation. *Renew. Energy* **147**:1209–1220. DOI:10.1016/j.renene.2019.09.088
68. Zou Z., Yan W., Gong H., et al. (2019). Quantifying the performance advantage of the novel passive air cooling system for PV array and system structure optimization. *Appl. Therm. Eng.* **149**:899–908. DOI:10.1016/j.applthermaleng.2018.12.085
69. Al-Amri F., Saeed F. and Mujeebu M.A. (2022). Novel dual-function racking structure for passive cooling of solar PV panels – thermal performance analysis. *Renew. Energy* **198**:100–113. DOI:10.1016/j.renene.2022.08.047
70. Adhikari R.C., Wood D.H. and Pahlevani M. (2020). Optimizing rectangular fins for natural convection cooling using CFD. *Therm. Sci. Eng. Prog.* **17**:100484. DOI:10.1016/j.tsep.2020.100484
71. Zheng Y., Miao J., Yu H., et al. (2023). Thermal analysis of air-cooled channels of different sizes in naturally ventilated photovoltaic wall panels. *Buildings* **13**:23002. DOI:10.3390/buildings13123002
72. Yuan F., Yin Z., Zhao N., et al. (2025). Experimental and numerical analysis of phase change material-based photovoltaic/thermal system with dual-parallel cooling channels. *Sol. Energy Mater. Sol. Cells* **286**:113563. DOI:10.1016/j.solmat.2025.113563
73. Wu S. (2019). Research progress of photovoltaic thermal management system based on phase change materials. *Refrig.* **38**:51–56. DOI:10.3969/j.ISSN.1005-9180.2019.03.011
74. Naqvi S.N.R., Haider M.Z., Jin X., et al. (2025). Investigation of thermal and mechanical performance of composite PCM mortar incorporated with graphene nanoplatelets. *Constr. Build. Mater.* DOI:10.1016/j.conbuildmat.2025.140576
75. Khan Z., Jamil F., Nasir M.A., et al. (2025). Experimental analysis of a double pass solar air collector using phase change materials integrated with nanoparticle. *J. Therm. Anal. Calorim.* **150**:5303–5318. DOI:10.1007/s10973-025-14007-z
76. Park J., Kim T. and Leigh S.-B. (2014). Application of a phase-change material to improve the electrical performance of vertical-building-added photovoltaics considering the annual weather conditions. *Sol. Energy* **105**:561–574. DOI:10.1016/j.solener.2014.04.020
77. Tan Jian Wei N., Jian Nan W. and Guiping C. (2017). Experimental study of efficiency of solar panel by phase change material cooling. *IOP Conf. Ser.: Mater. Sci. Eng.* **217**:012011. DOI:10.1088/1757-899X/217/1/012011
78. Biwole P.H., Eclache P. and Kuznik F. (2013). Phase-change materials to improve solar panel's performance. *Energy Build.* **62**:59–67. DOI:10.1016/j.enbuild.2013.02.059
79. Hasan A., McCormack S.J., Huang M.J., et al. (2015). Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates. *Sol. Energy* **115**:264–276. DOI:10.1016/j.solener.2015.02.003
80. Singh P., Mudgal V., Khanna S., et al. (2020). Experimental investigation of solar photovoltaic panel integrated with phase change material and multiple conductivity-enhancing-containers. *Energy* **205**:118047. DOI:10.1016/j.energy.2020.118047
81. Wang F., Li Z., Liu M., et al. (2023). Heat-dissipation performance of photovoltaic panels with a phase-change-material fin structure. *J. Clean. Prod.* **423**:138756. DOI:10.1016/j.jclepro.2023.138756
82. Chilbule P.V., Dhole L.P., Chavhan G.R., et al. (2025). Optimization of heat pipe used for thermal management of photovoltaic panel. *Trans. Indian Natl. Acad. Eng.* **10**:171–181. DOI:10.1007/s41403-024-00513-3
83. Wu S.-Y., Zhang Q.-L., Xiao L., et al. (2011). A heat pipe photovoltaic/thermal (PV/T) hybrid system and its performance evaluation. *Energy Build.* **43**:3558–3567. DOI:10.1016/j.enbuild.2011.09.017
84. Gang P., Huide F., Jie J., et al. (2012). Annual analysis of heat pipe PV/T systems for domestic hot water and electricity production. *Energy Convers. Manage.* **56**:8–21. DOI:10.1016/j.enconman.2011.11.011
85. Hou L., Quan Z., Zhao Y., et al. (2016). An experimental and simulative study on a novel photovoltaic-thermal collector with micro heat pipe array (MHPA-PV/T). *Energy Build.* **124**:60–69. DOI:10.1016/j.enbuild.2016.03.056
86. Jirapongphatai S., Asanakham A., Deethayat T., et al. (2023). Electrical and thermal performance analysis of photovoltaic module having evaporating surface for cooling. *Energy Rep.* **9**:4734–4748. DOI:10.1016/j.egyr.2023.03.117
87. Chandrasekar M. and Senthilkumar T. (2015). Experimental demonstration of enhanced solar energy utilization in flat PV (photovoltaic) modules cooled by heat spreaders in conjunction with cotton wick structures. *Energy* **90**:1401–1410. DOI:10.1016/j.energy.2015.06.074
88. Lucas M., Aguilar F.J., Ruiz J., et al. (2017). Photovoltaic evaporative chimney as a new alternative to enhance solar cooling. *Renew. Energy* **111**:26–37. DOI:10.1016/j.renene.2017.03.087
89. Malvika A., Arunachala U.C. and Varun K. (2022). Sustainable passive cooling strategy for photovoltaic module using burlap fabric-gravity assisted flow: A comparative energy, exergy, economic, and enviroeconomic analysis. *Appl. Energy* **326**:120036. DOI:10.1016/j.apenergy.2022.120036
90. Dida M., Boughali S., Bechki D., et al. (2021). Experimental investigation of a passive cooling system for photovoltaic modules efficiency improvement in hot and arid regions. *Energy Convers. Manage.* **243**:114328. DOI:10.1016/j.enconman.2021.114328
91. Li F., Lin H., Sui Z., et al. (2026). Multi-scale Optimization on Interfacial Evaporative Cooling for Photovoltaic Performance Enhancement. *Adv. Sci.*:e75120. DOI:10.1002/advs.75120
92. Su Y., Gu R., Li Y., et al. (2026). Seawater Interfacial Evaporation in Composite Gel Enables Photovoltaic Cooling, Simultaneous Seawater Desalination, and Enhanced Uranium Extraction. *Adv. Funct. Mater.* **36**:2420651. DOI:10.1002/adfm.202420651
93. Huang M., Zhou H., Tang G.H., et al. (2024). The potential of radiative cooling enhanced photovoltaic systems in China. *Adv. Appl. Energy* **15**:100184. DOI:10.1016/j.adapen.2024.100184
94. Li L., Chen H., Xie Z., et al. (2019). Ultra-broadband metamaterial absorber for infrared transparency window of the atmosphere. *Phys. Lett. A* **383**:126025. DOI:10.1016/j.physleta.2019.126025
95. Li L., Wang B., Wu X., et al. (2025). Performance analysis of temperature-dependent near-field thermophotovoltaics with passive radiative cooling approach. *Renew. Energy* **248**:123102. DOI:10.1016/j.renene.2025.123102
96. Xie Y., Lai Q., Guo P., et al. (2020). Investigating the infrared spectral radiative properties of self-ordered anodic aluminum oxide for passive radiative heat dissipation. *Infrared Phys. Technol.* **109**:103438. DOI:10.1016/j.infrared.2020.103438
97. Gong Q., Chen J., Zhang Y., et al. (2025). Spectrally engineered coatings for steering the solar photons. *Adv. Mater.* **37**:e2502542. DOI:10.1002/adma.202502542
98. Jia S., Huang M., Jiang X., et al. (2025). Tandem daytime radiative cooling and solar power generation. *Cell Rep. Phys. Sci.* **6**:102343. DOI:10.1016/j.xcrp.2024.102343
99. Zhao B., Hu M., Ao X., et al. (2018). Performance analysis of enhanced radiative cooling of solar cells based on a commercial silicon photovoltaic module. *Sol. Energy* **176**:248–255. DOI:10.1016/j.solener.2018.10.043
100. Zhao B., Lu K., Hu M., et al. (2022). Radiative cooling of solar cells with micro-grating photonic cooler. *Renew. Energy* **191**:662–668. DOI:10.1016/j.renene.2022.04.063
101. Tang H., Zhou Z., Jiao S., et al. (2022). Radiative cooling of solar cells with scalable and high-performance nanoporous anodic aluminum oxide. *Sol. Energy Mater. Sol. Cells* **235**:111498. DOI:10.1016/j.solmat.2021.111498
102. Li Z., Ma T., Ji F., et al. (2023). A hygroscopic composite backplate enabling passive cooling of photovoltaic panels. *ACS Energy Lett.* DOI:10.1021/acsenergylett.3c00196.
103. Pu S., Fu J., Liao Y., et al. (2020). Promoting energy efficiency via a self-adaptive evaporative cooling hydrogel. *Adv. Mater.* **32**:e1907307. DOI:10.1002/adma.201907307
104. Li H., Ma J., Yan W., et al. (2024). Lithium-based water-absorbent hydrogel with a high solar cell cooling flux. *Renew. Energy* **235**:121277. DOI:10.1016/j.renene.2024.121277
105. Li F., Sui Z., Lin H., et al. (2026). Nature-Inspired Sustainable Cooling for Photovoltaics with Enhanced Temperature-Salinity Dynamics. *Adv. Funct. Mater.* **36**:e12696. DOI:10.1002/adfm.202512696
106. Fang H., Dang S., Kumar P., et al. (2025). Streamlined fabrication of an inexpensive hygroscopic composite for low maintenance evaporative cooling of solar panels. *Mater. Sci. Eng. R Rep.* **165**:101016. DOI:10.1016/j.mser.2025.101016
107. Sun Y., Wang Y., Zhu L., et al. (2014). Direct liquid-immersion cooling of concentrator silicon solar cells in a linear concentrating photovoltaic receiver. *Energy* **65**:264–271. DOI:10.1016/j.energy.2013.11.063
108. Zhu L., Boehm R.F., Wang Y., et al. (2011). Water immersion cooling of PV cells in a high concentration system. *Sol. Energy Mater. Sol. Cells* **95**:538–545. DOI:10.1016/j.solmat.2010.08.037
109. Elminshawy N.A.S., Osama A., Naeim N., et al. (2022). Thermal regulation of partially floating photovoltaics for enhanced electricity production. *Sustain. Energy Technol. Assess.* **53**:102582. DOI:10.1016/j.seta.2022.102582
110. Dörenkämper M., Wahed A., Kumar A., et al. (2021). The cooling effect of floating PV in two different climate zones. *Sol. Energy* **214**:239–247. DOI:10.1016/j.solener.2020.

11.029
111. Li F., Sui Y., Lin H., et al. (2025). Self-adaptive interfacial evaporation for high-efficiency photovoltaic panel cooling. *Device* **3**:100569. DOI:10.1016/j.device.2024.100569
112. Kim S., Park J.H., Lee J.W., et al. (2023). Self-recovering passive cooling utilizing endothermic reaction driven by water sorption. *Nat. Commun.* **14**:2374. DOI:10.1038/s41467-023-38081-9
113. Ahmadi Moghaddam H., Tkachenko S., Yeoh G.H., et al. (2023). A newly designed BIPV system with enhanced passive cooling and ventilation. *Build. Simul.* **16**:2093–2107. DOI:10.1007/s12273-023-1051-z
114. Lv S., Wu Y., Gu H., et al. (2024). Enhancing solar efficiency through simultaneous solar harvesting and radiative cooling. *Appl. Therm. Eng.* **241**:122320. DOI:10.1016/j.applthermaleng.2023.122320

## FUNDING AND ACKNOWLEDGMENTS

This work was supported by Basic Research Program of Jiangsu (Grant no. BK20250035, BK20240509), National Natural Science Foundation of China (Grant no. 52206092), the National Key Research and Development Program of China (Grant No. 2024YFF0508900), Major Basic Research Project of the Natural Science Foundation of the Jiangsu Higher Education Institutions (Grant no. 25KJA470006), and "Blue and Green Project" of Jiangsu Higher Education Institutions.

## AUTHOR CONTRIBUTIONS

Qianqian Jin: Conceptualization; Methodology; Investigation; Software; Writing-Original Draft; Visualization. Ming Yan: Methodology; Formal Analysis; Writing-Original Draft, Visualization. Chong Zhai: Conceptualization; Resources; Writing-Review & Editing; Supervision; Project Administration; Funding acquisition. Chenhan Liu: Conceptualization; Writing-Review & Editing; Project Administration; Funding acquisition. All authors contributed to the manuscript and approved the final version.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

## DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

## SUPPLEMENTAL INFORMATION

It can be found online at: https://doi.org/10.59717/j.xinn-energy.2026.100158