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Absorptive Materials -Based Cooling Technologies for Solar Thermal: A Review of Thermal Management Strategies and Performance Enhancements

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ABSTRACT

The growing need for utility-scale photovoltaic (PV) systems to advance environmental goals has heightened concerns about the costs of scaling and thermal control. Among all the technical problems linked to PV panels, increased temperatures are the key issue, causing reduced efficiency and module damage. When solar energy is not absorbed by the photocells, the PV module's surface temperature can rise much higher, especially in hot climates. This is especially problematic at air temperatures above 50 °C, as traditional natural convection is unable to efficiently cool the PV modules; hence, the Spanish solar PV harnessing system traps 30% of the energy in the PV modules compared to the original efficiency. Moreover, high surface temperature cause material degradation, resulting in earlier thermal failure, replacement, or the expense of disposing of the latter. This is why methods for enhancing thermal management within PV panels are among the most important aspects, and, combined with several technological advances, PV readily available and could potentially reduce the cost of solar energy in the near future.

1. Introduction

Solar panels produce electrical current by a process that emits heat at the solar panel surface, elevating its temperature above ambient temperature. If the temperature of the solar panels rises by at least 1 degree, the performance coefficient of the solar panels will increase significantly [1]. Consequently, the rise in outdoor temperature would be lower, and the efficiency of power generation from these solar panels would be higher. This is why everyone wants passive and active solar panel temperature-reduction technologies. In this research area, passive solar panel temperature-reduction technologies depend on the materials used and the type of cooling structures attached to the back side of the solar panels [2]. However, active solar panel temperature-reduction technologies are, in one way or another, associated with coolant flows in the cooling layers installed on the back side of the solar panels [2]. However, these studies are being conducted quite actively, though many rely on theoretical or experimental modelling. Because of this limitation, an empirical model has not been developed to select the properties of the most effective materials; designs of cooling structures and layers for both passive and active solar panel temperature-reduction technologies have not been proposed [3]. This is a self-healing structure for long-term, efficient, and effective cooling performance.

1.1. Background On Solar Energy

Merits: Solar panels convert sunlight into electricity, but they tend to heat up during use, which can affect their FW plug efficiency. Existing cooling methods used in industry-level applications rely on massive, intricate systems. This, as well as additional parasitic power losses for their creation and operation, takes energy away from the electric generation capacity [4]. Normally, when the temperature rises by 10 °C above the average 25 °C at which most solar applications work, the efficiency declines by 1%–3%. As widely

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acknowledged, any cooling system that cools panels ultimately elevates the conversion of the light into electricity [5].

It is not a new idea to try to convert sunlight into a form of energy usable for various purposes. The energy of sunlight has been used to drive chemical reactions in plants for millions of years [6]. Though it is a very complex process by which leaves can use the sun to transform the water ~~a~~ and carbon dioxide available in the atmosphere into oxygen, as well as naturally synthesized complex chemical compounds like glucose, with the help of naturally available vitamins and amino acids [7][8].

Table 1. Summary

Study	Material/Technique	System	Cooling Mode	Notes	Primary Citation
[9]	PV/T cooling (air, water, bi-fluid, nanofluid, others)	PVT	Active & Passive	Analyzes multiple PV/T cooling methods.	A review of PV/T system cooled using mono- and bi-fluids (Elsevier, 2024)
[10]	Recent PV cooling systems overview	PV	Passive & Active	Includes PCM comparisons (active vs passive).	Overview of Recent Solar Photovoltaic Cooling System (MDPI, 2024)
[11]	Enhancement strategies with a focus on cooling	PV	Various	Latest advances summarized.	Enhancing photovoltaic systems: comprehensive review (Elsevier, 2025)
[12]	Cooling & power enhancement systems	PV	Various	Consolidates recent advances.	Solar photovoltaic cooling and power enhancement systems (Elsevier, 2025)
[13]	Cooling techniques include. PCM-integrated natural water loops	PV / PVT	Passive & Hybrid	Extensive bibliography; economic aspects.	Comprehensive review on cooling of solar PV (MDPI Energies, 2025)
[14]	Hybrid PVT–PCM and PVT–NPCM	PVT	Passive/Hybrid	Focus on PCM-based hybrids.	IJLCT (OUP), 2022
[15]	Nanofluid-based PV/T cooling; MWCNT vs oxide	PVT	Active	Finds MWCNT nanofluid generally superior.	Performance evaluation of nanofluid-based PVT (PMC, 2024)
[16]	Nanofluids for PV/T thermal management	PVT	Active	Covers heat transfer enhancement mechanisms.	Nanofluids for PVT (PDF, 2024)
[17]	Cooling performance enhancement of PV systems	PV / PVT	Various	State-of-the-art overview.	AIP (2024)
[18]	Passive heatsinks & fins for PV	PV	Passive	Summarizes fin/heatsink designs.	Passive Cooling for PV Using Heat Sinks (2024)
[19]	Selective absorber coatings (spectral selectivity)	Solar thermal / potential PV passive	—	Materials & design for selective absorption.	A catalyst for enhanced solar energy conversion efficiency (Elsevier, 2024)
[20]	Mid/high-T selective absorber coatings	Solar thermal / CSP	—	Covers coating types & fabrication.	Review of spectrally selective absorber coatings (Elsevier, 2022)
[21]	Solar thermal selective coatings (STSCs)	Solar thermal; insights applicable to PV surfaces	—	Aging mechanisms & design strategies.	MDPI Appl. Sci., 2024
[22]	Spectrally selective absorbers (emerging materials)	Solar thermal; surface engineering	—	Recent advances & evaluation.	AIP Applied Physics Reviews, 2024
[23]	Cermet-based selective absorbers	Solar absorbers	—	Foundational review on cermets.	MIT DSpace PDF, 2014
[24]	Selective black coating (prototype test)	Solar absorber prototype	—	Experimental validation of selective coating.	J. of Materials Science & Green Energy, 2025

Study	Material/Technique	System	Cooling Mode	Notes	Primary Citation
[25]	Thermal management with PCM & fins (survey)	PV	Passive	Cites multiple PCM–fin containers.	Thermal management of PV module using PCM (PMC, 2024)
[26]	PCM in a finned container heat sink	PV	Passive	Experimental PV temperature reduction reported.	Solar Energy, 2020 (via PMC review)
[27]	PCM + natural water circulation	PV	Hybrid	Combines latent storage with a water loop.	Renewable Energy, 2021 (via MDPI Energies 2025)
[28]	Al2O3 nanofluid cooling for CPV	CPV	Active	Performance & sustainability gains.	Energy Science & Engineering, 2025
[29]	Hybrid nanofluid + 3D oscillating heat pipe	PV	Active	3D-OHP enhances heat removal.	Energy Reports (Wiley Hindawi), 2025
[30]	MWCNT vs oxide nanofluids (meta-analysis)	PVT	Active	MWCNT is often superior for PVT cooling.	PMC article, 2024
[31]	Novel finned heat sink + embedded PCMs	PV	Passive/Hybrid	The proposed geometry reduces PV temperature.	Case Studies in Thermal Engineering, 2025
[32]	Novel heat sink (PV-PWSFs)	PV	Passive	Lowered temp to 57.8 °C at 1000 W/m².	ASME J. Solar Energy Engineering, 2025
[33]	Metal foam fins & heatsinks	PV	Passive	Summarizes metal foam benefits.	ResearchGate review, 2025
[34]	Smart thermal management techniques	PV	Various	Environmental impacts and dust, wind, etc.	AIMS Energy review, 2025
[35]	Recent advancement in PV cooling	PV	Various	Survey of techniques above STC temperatures.	Preprints (2025)
[36]	Selective absorbers/emitters (steam gen & radiative)	Solar thermal	Passive radiative (contextual)	Links absorbers and radiative cooling concepts.	Small (Open-access PMC), 2020

On average, solar energy constitutes the main energy resource on Earth. Other than energy stored in the organic matter, examples include radioactivity and geothermal energy from fossil fuels, and so on, all of which were generated from the energy trapped in sunlight. The foundation of solar energy conversion, nonetheless, can be considered rather fundamental and uncomplicated. The atmosphere of the Earth is analogous to a window, which lets in only that part of the sun's spectrum that is useful to life. A very small percentage of the total solar energy incident on the planet actually reaches the surface [37].

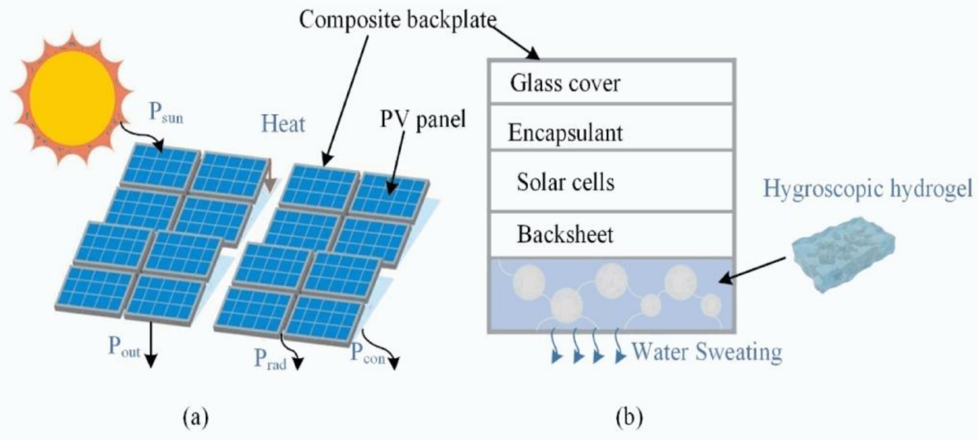

Figure 1. Cooling Mechanism of PV Panels Using Hygroscopic Hydrogel and Composite Backplate

Figure 1 shows how the PV panel cooling mechanism works using hygroscopic hydrogel and composite back plate. The fraction of sunlight in the incident solar spectrum ranges from approximately 0.3 µm to 2.5 µm. Solar energy can be directly utilized in three primary ways: photothermal, photovoltaic, and photosynthetic. In photothermal conversion, sunlight provides energy to heat a working fluid to high temperatures. In photothermal conversion, sunlight the energy is used to heat a working fluid to high temperatures [38]. The working fluid can be a gas, a liquid, or solid particles. These are the essential components of a solar-powered steam cycle or energy production system. In photovoltaic conversion, the energy of photons in the solar spectrum is used to generate electron-hole pair excitations. This forms a solar panel, or photovoltaic panel, and when connected to an external circuit, forms a solar cell [39]. Upon excitation by sunlight, the charges are separated by an external electric field, allowing them to flow through an external circuit, where they can be harvested and stored or consumed by electrical devices. Finally, in the most complex photosynthetic process, sunlight energy is used to split water into oxygen and to collect the generated electrons to build sugars and fats [40].

1.1.1. Common Types of Solar Panels

The four main categories of existing solar cells are monocrystalline silicon, polycrystalline silicon, thin-film, and back-contact. All are the same devices that can convert sunlight into electricity, but with varying efficiencies or costs. Monocrystalline solar cells are among the most effective of the four, with conversion efficiencies up to 20 percent. There are two main types of solar cells – polycrystalline and thin-film solar cells – that have lower production costs but lower efficiency than monocrystalline solar cells [41]. Monocrystalline and polycrystalline solar cells are the two most commonly used types of solar cells due to their lower production costs and high commercial efficiency. Hence, we have back-contact solar cells, as the costliest with prices as high as $3.3 per watt, while the efficiency level ranges from 22%. The use of these technologies is high due to their costs, and as a result, they are used only in satellites and high-altitude aircraft [42].

Present a passive cooling system which works by phase changes and does not require power to operate [43]. The cooling system involves a hydrogel heat-exchange element incorporated into a hydrophilic, porous material that swells and deswells in response to changes in temperature and to sunlight-induced evaporation drawing heat from the solar panels. This system is a basic cooling arrangement, compact and efficient and can be integrated into existing silicon PV systems to reduce operating temperatures, thereby improving PV system performance manner. It is believed that cooling the solar panels can enhance the units' efficiency, particularly in very hot, sunny climates, and also provide more reliable and effective utility [44].

1.2. The Importance of Cooling in Solar Energy Efficiency.

The use of water-based coolants is critical in across a wide range of cooling technologies. The hydrogel-based cooling technology can be described based on the phase of water, including solid phase, fluid phase, and vapor phase, therefore; various technology strategy developments can be implemented for the purpose of obtaining effective performance [45]. Each of ice, liquid water, and water vapor plays its part in heat transport from the solar panel to the environment. When the solar panel is hot and placed on ice, heat is transferred from the solar panel to the ice melting it. The produced liquid water or melt water will cool the solar panel for some time through phase change, releasing the latent heat of fusion and then warm up to the solar panel's temperature (which is high) [46]. Following, this the water vapor can also cool by evaporating on the panel.

In general, hydrogel-based cooling technologies for solar panels can be divided into four categories, according to the respective phases of water at different stages: There are four forms of heat transfer cooling Technologies namely; (i); the ice cooling technology, (ii); the liquid water-cooling technology, (iii); the water vapor generation-based cooling technology and (iv); the compound phase variation cooling technology [47]. They can offer higher efficiency across all use cases, depending on specific market or climate requirements. The research section of this paper provides an exhaustive review of hydrogel-based cooling technologies applied to solar panels at the two sites.

1.3. Comparison of Hydrogel Cooling Systems with Traditional Cooling Methods

Hydrogel-based cooling modules offer strong cooling performance and excellent water retention, making them suitable for passive cooling of solar panels. Based on that, hydrogel cooling modules have now been investigated as possible new alternatives to liquid cooling and passive methods [48]. A flat-plate PV/T collector has been simulated using a novel hybrid model that linked the electrical and thermal element models to analyze solar PV/T systems and the integrated thermal energy storage water. The effect of shading the PV cell area on the thermal performance is presented. This performance is significantly increased through the use of water-cooled hybrid TSAS [49].

By reviewing a wide range of operations, thermal management strategies for solar PV modules have been analyzed. This study compares hydrogel-based cooling technology with traditional cooling methods and provides a detailed summary. Finally, it is observed that traditional cooling strategies for solar modules have critical issues, such as high-water pump energy consumption and PV module degradation [50]. To further improve the cooling performance, some researchers use nanomaterials to enhance the thermal conductivity of the circulating fluid. A lot of useful information can be obtained to design a suitable hydrogel cooling system. The final part some also addresses challenges and prospects in this research field. In recent years, the use of solar energy for electricity generation has been increasing [51].

1.4. Definition And Properties of Hydrogels.

A hydrogel is a kind of polymer network with numerous pores. Nearly one-half of its weight is made-up of water, and the hydrogel can replicate some tissue structures and paradigms. Because the bonding restrictions and the higher cross-linking degree in the hydrogel limit the polymer chains' macromotion, the hydrogel exhibits ~~a~~ viscoelastic behavior. The hydrogel's pore and chemical structures can be modified to better simulate biological tissue properties and achieve the desired functionalities [52]. Even though hydrogels can share many similarities, there are several underlying differences due to their complex architectural and chemical features. The nature of such diversity can be broadened beyond recognition as primarily application-specific and economic, for uses in health, water management, energy, biodefense and security, food, and agriculture. Independently, energy qualities can also benefit from channeled hydrogels in the presence of graphite [53].

The content and pore size of the hydrogel together determine its morphology. Different combinations can yield distinct morphologies. The connections between the polymer chains form a network structure and a large number of pores. These pores can interact with water molecules of different sizes present in the atmosphere. As the temperature rises, the segments tend to unfold and coil, as the temperature~~,~~ potentially leading to a local accumulation at the contact point and, keeping the surface much cooler [54]. To this end, the capillary network's connectivity and randomness are important. Additionally, to ensure the most efficient heat transport, the interactions within the water phase need to be orchestrated. Consequently, these properties resemble those of natural tissue. To ensure rapid blood gas exchange, the natural capillary network was randomized. Heat can be easily exchanged thanks to the support that fiber network structures can provide [55].

1.5. Purpose And Scope of The Review.

Over the last couple of decades, environmental and energy conservation concerns have attracted significant attention from governments and the scientific community. This has resulted in the development of many waste-to-energy processes, with the construction of vital frameworks that can be boosted by naturally available resources. One such significant asset is the sun, a prime source with no limit regarding the energy it produces. As a result, advances in photovoltaics and legislative policies have driven significant growth in the solar power industry has [56]. Solar power, therefore, offers an economically savvy way to reduce customer-modified rates. Over past couple of decades, regions with efficient solar panel installations have grown stronger. Parallel to the scaling of solar power technologies and industries, reductions in solar cell costs and increases in power conversion efficiencies have significantly reduced the cost per watt of solar energy [57]. In light of this reduction, the present work explores a new, efficient cooling technique for solar panels, and no study has discussed the specific use of hydrogels in such a strategy. The aim of the present study, therefore, is to propose a model that employs hydrogel-based cooling systems to reduce the working temperatures and the heat load of the solar panels [58].

1.6. Performance Outcomes Reported (Summary of Reported Ranges)

Across these material classes, reported operating temperature reductions vary widely (from a few degrees to tens of degrees, depending on configuration, solar irradiance, and environmental humidity). For hydrogels, experimental studies commonly report multi-degree reductions (e.g., single-digit to low-teens °C) under outdoor testing and modelled scenarios; some engineered hydrogel membranes report larger drops under controlled tests. Nanofluid and nanoparticle-reinforced fluids or coatings typically exhibit improved heat transfer coefficients and modest to significant reductions in panel temperature, depending on concentration and flow conditions. Radiative solutions report sustainable daytime cooling power densities when spectral design is optimized.

1.7. Durability, Scalability, and Practical Considerations (Descriptive Notes)

Authors frequently note material-lifetime and environmental-exposure challenges: hydrogels may dry out, degrade, or change their swelling behavior over time; nanoparticle suspensions require stability control to prevent settling or fouling; porous scaffolds must withstand mechanical and environmental stresses; and photonic radiative emitters must retain spectral properties under weathering. System-level studies emphasize that the integration strategy (coating, removable attachment, or behind-panel emitter) heavily influences maintenance, retrofitting feasibility, and scalability.

1.8. Concluding Descriptive Observations

The literature presents a diverse set of absortive material strategies, ranging from hydrogels and nanofluids to metamaterials and radiative emitters, each demonstrating practical routes to lower absorber temperatures and improved solar-to-useful energy conversion in experimental or simulated settings. The current body of work is largely descriptive: authors report measured temperature drops, heat-transfer coefficients, and initial durability observations, while system-level long-term field studies and standardized durability protocols remain comparatively fewer. For a descriptive review, the emphasis remains on reporting what each study built and observed (materials, test conditions, temperature/efficiency results), leaving detailed method-by-method ranking for contexts that require trade-off analysis.

2. Mechanism of Hydrogel Cooling

2.1. Absorbent Material-based Cooling Systems

Hydrogel-based cooling systems for solar panels primarily take the form of cooling coatings, hydrogel cooling boxes, and embedded hydrogel channel devices. The cooling coating method is less complex and relatively more mature; this technique is usually used for solar modules and collectors. The hydrogel cooling container and embedded hydrogel channel technology are designed to include: the passive technology could realize temperature containment and storage because of the natural working performance and the regulation of the phase transition of the hydrogel; and the active cooling system could lower the solar panel temperature by using a cooling device in the film of the water curtain or in a water tank [59]. Also, there are a variety of related technologies including water-tube heat exchangers and microfluidic channels. The embedded hydrogel cooling technology is more complex and is mainly used for solar absorbers [60].

Although relatively complicated, it could significantly reduce hydrogel loss. The active hydrogel cooling technology of the newly built solar panels was adapted to the local rainwater, with in the hydrogel encapsulation covering 20% of the surface area. This work shortened the network operation of the cooling rate of the solar thermal system from 7 hours to a maximum of 20 minutes, and the power generated by the solar thermal system increased by 20.3%. When the cooling system was fully covered, the power generation of the photovoltaic cells increased by [61]. Alarmingly, the moisture in the hydrogel could be collected by the system's infrared solar system. Although not clear, the system is often contained within a polyethylene outer layer of hydrogel to create a heat-insulating device maintains thermal contact with the solar panel. The spatial heat loss from the available system to the air mainly depends on the thermal conductivity of the hydrogel, and the close interior of the solar panel is sensitive to the equipment's operation [62].

Hydrogels, water-rich polymer matrices with high heat capacity and moisture-management capabilities, are a major class of absorptive materials under investigation for passive cooling of solar absorbers and PV/PVT devices. Several experimental works reported practical cooling attachments using either hydrogel beads or thin hydrogel films applied to or placed near PV modules. An experimental study of hydrogel beads in bed configurations demonstrated meaningful temperature reductions under outdoor conditions and characterized how packing and water content influence cooling performance.

More recent modelling and experimental work extended the use of hydrogels to hygroscopic and thermos responsive systems for photovoltaic cooling, proposing coupled heat–mass transfer models and identifying environmental/aging factors that affect long-term performance. A hygroscopic hydrogel system for PV cooling was modelled and experimentally validated, highlighting both potential temperature reductions and the need to account for hydrogel water transport during seasonal operation.

Innovations aimed at boosting effectiveness include lightweight, thin hydrogel membranes and composite hydrogels with embedded photothermal agents. A very recent study reported a lightweight hydrogel system that lowered PV operating temperature by large margins in controlled testing (reductions of up to tens of degrees Celsius in some tests), suggesting significant potential to improve electrical conversion and reduce thermal degradation pathways.

Researchers have also developed multifunctional photothermal hydrogels for solar-driven evaporation and thermal regulation, in which the hydrogel simultaneously absorbs solar radiation and facilitates evaporative cooling. These designs often emphasize water transport, cycle stability, and the trade-off between photothermal absorption and radiative/evaporative cooling routes.

2.2. Nanoparticle Enhanced Absorbers and Nanofluids

Another active route is adding nanoparticles either into coatings, selective absorber layers, or heat-transfer fluids to improve radiative/absorptive properties and thermal transport. Studies of Al_2O_3 nanoparticle-enhanced ionic liquids and nanofluids report increases in heat transfer coefficient, improved solar-thermal capture, and changes in stability and viscosity that must be managed for real systems. Experimental CSP and PVT investigations showed that nanofluid cooling can reduce panel temperatures and raise usable thermal output, though design trade-offs (particle fraction, dispersion stability, pump energy) were emphasized.

At the absorber-coating level, nanostructured multilayer and refractory nanolayer absorbers (e.g., $TiN/Al_2O_3/TiN$ and similar meta-surface stacks) have been engineered to enhance selective absorption and thermal stability under high flux; such thin-film and meta-surface approaches alter spectral absorption while seeking to limit unwanted thermal emission. These designs are mainly material-engineering solutions that target long-term stability and high absorption across the solar spectrum.

2.3. Porous, Aerogel, and Bio-Inspired Absorptive Materials

Porous ceramics, aerogels, and bio-inspired fibrous materials offer distinct balances of thermal insulation, light trapping, and water management. High-porosity photothermal aerogels and rigid porous evaporators have been reported for interfacial solar evaporation and thermal regulation; they aim to localize heat at the absorption interface while permitting evaporative cooling or thermal insulation where desirable. These studies typically report strong light absorption, controlled heat localization and improved evaporation rates; practical deployment focuses on the mechanical robustness and hydrophilicity of the porous scaffold. Several cellulose- and natural-polymer-based hydrogels and composites combine low-cost bio-derived materials with photothermal fillers to create adaptable absorbers that balance sustainability and performance; such approaches highlight lifecycle considerations in absorber selection.

2.4. Radiative and Photonic Cooling Integrated with Absorptive Materials

Radiative cooling techniques engineered emitters that radiate thermal energy into outer space through the atmospheric transparency window are increasingly combined with absorptive strategies. Reviews and modelling studies on radiative cooling for vertical panels demonstrate that passive daytime radiative cooling can lower operating temperatures without active energy input, either by placing radiative emitters behind the panels or by integrating selective photonic structures on the panel surface. Several recent reviews cover principles, material designs, and prospects for integrating radiative cooling with solar heating systems.

Combined devices that integrate radiative cooling and photothermal absorption aim to be “dual-mode” harvesters of sunlight when needed and radiative coolers when cooling is desired. Experimental demonstrations and simulations show that such synergy can yield on-demand thermal management, but practical implementation requires careful spectral design to avoid mutual destruction of daytime solar absorption and mid-IR emission.

3. Discussion of Evaporative Cooling and Thermal Conductivity

Over recent years, growing environmental concerns and energy crises have led to greater reliance on solar energy to mitigate these problems. As a result, solar panels are being widely equipped across various applications. The power output of solar panels can be significantly affected elevated temperatures, necessitating more effective thermal management strategies [63]. Maximum output power will be achieved in solar cells when the temperature is kept low enough, while the cost of the cooling technology should be competitive enough to maintain the technology’s competitiveness. Hydrogel-based cooling technology is a promising solution for addressing such problems [64].

Many studies have been conducted on the application of water-based heat exchangers on the back face of photovoltaics, but less attention has been paid to strategies for the front face of the panels. Simple film-evaporation methods are typically employed, but icing problems at very low temperatures can persist for several weeks and continuously remove the system from operating conditions [65]. This system also requires chemicals and water, which increase complexity and cost. To address all these issues, researchers have employed various hydrogels as the working fluid, absorbed in a film spread over a porous surface. Compared with other strategies, this configuration offers a self-renewing low-temperature level over nearly the entire operating temperature range of solar panels, at low cost and without icing issues [66].

4. Types of Hydrogels for Solar Panel Cooling

4.1. Superabsorbent Hydrogels

Different techniques are employed to produce a range of hydrogel matrices with suitable features for various applications. As the material properties (related to crosslink density, molecular weight between crosslinks, chain stiffness, and configurational entropy), gelation kinetics, and physical form of hydrogels (particulate, nanogel, bulk, or membrane) highly affect the thermal performance of the synthesized hydrogels, these parameters should be carefully controlled for developing hydrogels for CSP [67]. On the other hand, temperature sensitivity, or the thermos physiological performance, is crucial for cooling. The techniques for making bulk hydrogels, microgels, and nanogels, have been studied for specific drug-targeting and delivery applications. Similarly, in this section, the state-of-the-art studies on these three forms of hydrogels will be reviewed based on the techniques used to produce them [68].

4.2. Temperature-Responsive Hydrogels.

Numerous studies employ naturally derived biopolymers to synthesize hydrogels. They use biopolymer networks as a matrices and chemically or physically modify them to impart temperature responsiveness. For example, cellulose, chitosan, starch, alginate, pectin, and gelatin are widely studied natural biopolymers. Their use as raw materials for the synthesis of hydrogels is almost entirely achieved using an easy-to-design, simple method that employs crosslinkers, additives, or post-treatment [69]. Stimuli-responsive hydrogels prepared by biodegradable polymers have been reviewed. Synthetic polymers are often used to produce hydrogels with specific properties, as biopolymers are particularly sensitive to dissolution. Unsuitable mechanical properties, pH sensitivity, hydrolytic instability, and immunogenicity can make them unsuitable for biomedical and industrial applications [70]. Crosslinking and polymerization are the two principal pathways, though many methods can be used to produce hydrogels from synthetic materials. In addition to these conventional techniques, many innovative methods have been developed that add superior features and strength to hydrogels. For example, micro and nanoparticulate hydrogels implanted with different physicochemical properties can be synthesized for diverse applications [71]. Moreover, a prototype biomaterial with an appropriate molecular weight between crosslinks and crosslink density can be designed to exhibit tunable sensitivity.

4.3. Performance Evaluation Metrics for Hydrogel Cooling Technologies

As an advanced cooling technology for solar panels, hydrogel-based cooling significantly improves temperature uniformity across the photovoltaic panel and directly increases output power. In addition, it is very important for system development to comprehensively evaluate the thermal performance of hydrogel-based cooling systems. In recent years, significant progress has been reported in research on advanced cooling technologies for solar panels. To date, a discussion of the metrics for comparing and evaluating the performance of cooling systems appears to be lacking [72].

Several thermal management indicators were suggested to comprehensively evaluate the performance of hydrogel-based cooling technologies. Performance evaluation indicators with different emphases, derived from identical metrics, were presented to cover all aspects of thermal performance. Among these, the pressure loss penalty factor was introduced to give a comprehensive evaluation of the thermal and flow features [73]. There is no dependence on module power. The present work could serve as a reference for the performance evaluation of hydrogel-based cooling technologies and provide guidelines for large-scale high-volume replacement of conventional materials.

4.4. Design Considerations for Hydrogel Cooling Systems

Ensuring a stable water supply and tight contact between the hydrogel and solar panel are crucial for achieving efficient solar panel cooling. During the operation of solar panels integrated with hydrogels, water vapor can either rise directly with the air-carried evaporated water vapor or leak from the side of the hydrogel container [74]. As water in the hydrogel gradually evaporates, the internal stress in the hydrogel wall can compromise its structural integrity, thereby inducing fabrication failure. Electrostatic spinning, electrochemical and biodegradable methods, multi-scale structures, and reinforcement of the hydrogel can be in the surface, middle, and bulk dimensions to strengthen the overall mechanical performance, prevent surface water film formation, enhance the water transport rate and structural stability, shorten the time required for startup and shutdown, and reduce internal parasitic heat [75].

Table 2. Design Considerations for Hydrogel Cooling Systems

Category	Design Consideration
1. Material Selection	Hydrogel Polymer Base
	Water Absorption Capacity
	Optical Transparency
2. Thermal Properties	Thermal Conductivity
	Latent Heat Storage
	Evaporative Cooling Efficiency
3. Mechanical Properties	Flexibility and Adhesion
	Durability (UV & Heat Resistance)
	Self-Healing / Rehydration
4. Environmental Conditions	Ambient Temperature & Humidity
	Rain & Dust Resistance
5. Integration with Solar Panels	Attachment Method
	Weight and Load
	Replacement or Refilling Design
6. Longevity & Sustainability	Water Retention Over Time
	Eco-Friendliness
7. Multi-functionality	Antireflective / Dust-Repellent Properties
	Hybrid Cooling (Evaporation + Radiative + PCM)

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To protect the excellent water-storage characteristics of the hydrogel, construction barriers are used to separate the photothermal and optical effects of the solar panel, which are considered the main driving forces of the moisture evaporation process, from the fresh water. The small thermal conductivity of the blanket sheath can also minimize the blowing of the entire panel structure, especially if the storage caliber requirement for fresh water is not very strict [76]. In this limited water storage capacity of the enclosure system, membrane distillation driven by the temperature difference between the solar panel system and the air, in combination with the external solar collector, which works as a solar chimney, can effectively regenerate and recycle the distilled and transferred fresh water during the operation cycle [77]. To avoid the potential risks of microorganisms, algae, and other pollutants blocking or penetrating the hydrogel, which would impact the optical properties and photocatalytic activity of the solar panel, an antifouling or anti-adhesion strategy using operating surfactants or external biofouling-release materials should be applied as a functional coating or membrane [78].

5. Case Studies

5.1. Hydrogel Modification for Enhanced Cooling Performance

To further boost the hydrogel-based cooling performance, many modification techniques have been explored, including hydrogel formulation and gelation, employed strategies, and optimization of preparation conditions. With the increasing number of hydrogels reported, classification and summarization are necessary to provide insights into the design and acquisition of high-cooling hydrogel materials in the field. In this section, a comprehensive overview of the development and modification techniques of the existing hydrogels employed for solar panel cooling will be provided [79]. The strategies include in situ preparation of hydrogels, multiple-ingredients reinforcement, physical or chemical modification of hydrogels, hydrogel-based 3D printing, and intelligent responses to external stimuli, which address the most recent modifications aimed at developing improved hydrogels.

Acrylic acid and 3,6-dioxa-1,8-octane diol are the monomeric hydrolysable macromers, with acrylamide, gelatin, and sodium tetraborate as the physical cross-linking monomers; the resulting hydrogel exhibits triple responsiveness to temperature, pH, and salt concentration. The quadruple networks hydrogel was prepared by free-radical polymerization of functional monomers and physically crosslinked gelatin, followed by a final step of polyphenol/hydrogen-bond physical crosslinking; the presence of gelatin increased the toughness and plasticity [80]. There are other polyelectrolytic hydrogels, such as chitosan-based, carboxymethyl cellulose-based, and diamino polythene oxide-based, that can regulate humidity and exhibit adaptable deformability. For instance, zwitterionic sulfopropylbetaine groups and hydrophobic 2-linoleyl groups containing polymerizable double bonds of ultralong alkyl chains were employed as comonomers for the free-radical polymerization; the resultant hydrogel can be photocured in an ultraviolet glycerol solution [81]. Characterizations and applications of these hydrogels were fully discussed. Due to the diverse environmental and ecological needs for hydrogels, our intent is that these studies spur the further design of intelligent, responsive hydrogels that meet benchmark solution requirements across the field.

5.2. Applications of Hydrogel-Based Cooling Technologies

In this section, the application of hydrogel-based cooling technologies in solar panels and their performance enhancement will be discussed. Solar panels require efficient cooling systems to maintain their operating temperature in the ideal range for better device performance. Hence, a comprehensive review of thermal management strategies will be conducted, with a focus on performance enhancement. The major findings, challenges, and future work will also be discussed afterward [82].

Solar energy is one of the most promising renewable energy sources for addressing the current global energy crisis. The energy shortage can be addressed within a short time by using solar energy, thereby reducing environmental pollution. Nevertheless, solar panels, traditionally used for energy conversion, convert less than 35–40% of absorbed solar radiation ~~to~~ into electrical power with the remaining energy radiating back into the environment [83]. The performance degradation of solar modules will be largely affected by rising local temperatures. For example, a 50 °C rise in temperature within a crystalline silicon solar panel can decrease energy yields by 2.5–4.5% and 16.5–20% in a single year and over a 20-25-year operating lifetime, respectively. As a result, a thermal management method is essential to maintain the solar panels' operating temperature within the ideal range [84].

5.3. Hydrogel-Based Cooling Systems for Photovoltaic Cells

Faced with rising global energy consumption and environmental challenges, solar cells increasingly widely used worldwide. As an important type of solar energy utilization technology, solar cells have been widely studied and applied. Photovoltaic cells are mainly composed of solar cells, transparent covers, and backs. There are many types of solar cells, of which the most prevalent are bulk photovoltaic cells: monocrystalline, polycrystalline, and amorphous. Among them, monocrystalline silicon solar cells have the highest photoelectric conversion efficiency. Owing to the working mechanism of photovoltaic cells, solar cells convert sunlight into electricity [85]. In the photovoltaic process, due to the photoelectric conversion, a significant amount of sunlight turns into heat, which might eventually cause solar cells to have an operating temperature of about 304 K to 320 K. This sometimes might cause hot spots and local overheating, increasing the possibility of solar cell damage and decreasing cell operating efficiency [86].

To solve the solar cell overheating problem, using hydrogel heat battery cooling units to create a hydronic system enables the battery to be cooled during the day and to release cold during the night. In this case study, to demonstrate the practical application of optimal architecture and materials for insulation in variable conditions, indoor tests and numerical simulations are used [87]. The proposed power station can absorb more than 14 Wh of solar energy over a 12-hour sunny day and release approximately the same amount of heat for 10 hours during a 12-hour night. Such a system can reduce urban heat island effects, increase photovoltaic energy yield, and provide valuable building insulation during the heating season.

5.4. Hydrogel-Based Coatings for Solar Panels

Cracks and damage caused by traditional coating technologies limit the practical application of coating technology on solar panels. By taking the unique properties of hydrogels, such as super water absorbability, efficient thermal insulation, and good radiation resistance into account, we propose coating hydrogels on the surface of solar cells to enhance the water-cooling effect and minimize temperature-induced damage. When cooling requires energy consumption, this conflicts with the energy-saving effect of hydrogel-based cooling. Magnetic nanoparticles can be used to actively control ~~of~~ the cooling behavior of hydrogels under a magnetic field [88]. The hydrogel-based external passive thermal control or internal active thermal control can eventually be selected based on the local temperature changes induced by solar radiation, providing a new strategy for the development of future solar cells. Recently, with declining costs and improving power generation efficiency, solar panels have advanced rapidly. As the efficiency of solar panels improves, however, the conversion rates of the photoelectric conversion module reduce [89]. Specifically, when the temperature of the solar panel exceeds 25 °C, a 0.5–0.7% decrease in the photoelectric conversion rate occurs for every 1 °C increase in temperature. Presently, traditional methods of solar panel cooling mainly include circulating water, heat pipes, and phase-change cooling equipment [90]. These cooling methods require constant use of water, groundwater, etc., and also entail high energy consumption. In addition, traditional heat pipes in direct contact with the back of solar panels are prone to various damage, and phase change cooling equipment is unsuitable for small - and medium-sized solar power stations.

5.5. Hydrogel-Enhanced Heat Pipes for Solar Panel Cooling

For solar panel cooling enhancement, hydrogel-supported heat pipes offer a key advantage over conventional open heat pipe architectures, as they prevent water loss and contamination by eliminating direct access to the inner vapor. The prepared hydrogel with an appropriate composition and microstructure exhibits good performance in water adsorption and transport. To date, hydrogel-encapsulated heat pipes have been reported to achieve efficient heat dissipation from concentrated photovoltaic receivers [91]. The fabrication of an agar and aluminum nitride composite hydrogel-coated copper oscillating heat pipe achieved effective dissipation of 2 W/m² when the water temperature inside the pipe was controlled at approximately 50 °C, with a temperature similar to or slightly lower than that of the cooling treatment without the hydrogel coating [92].

When agar hydrogels were used as permeable membranes for nearly all active/distilled water passive cooling systems of concentrated photovoltaic cells, a single-phase agar (5 wt%) solution was dropped into a colloid to induce visible cross-linking. The formed solution could be transferred to a 2 mm-thick hydrogel film within 24 hours; such a hydrogel film could allow more uniform water release. This cooling system exhibited no migrating vapor behavior and unhindered communication from the vapor region manifold to the soil, as the revealed agar solution was located between the top of the hydrophilic yarn and the upper surface of the hydrogel layer, serving as an integrated synthetic hydrogel/wick composite [93]. The developed passive cooling system enabled strict vapor confinement in the longitudinal direction, balanced the evaporation differences across the cooling channels, stabilized the displacement of the boiling boundary surfaces, prevented construction failure, and maintained solar-thermal energy transformation performance. This permeable membrane cooling system had the minimum weight, was mainly made of natural materials, and exhibited efficient heat dissipation [94]. Hydrogel-oscillating heat pipes described in the aforementioned section were widely used to cool concentrated photovoltaic cells in a passive solar water collector for simultaneous electricity generation and cooling.

5.6. Hydrogel-Embedded Heat Exchangers for Solar Panels

In contrast to nuclear, coal, or natural gas power plants, solar panels require a relatively large number of industrial buildings. In addition, many urban construction companies allocate a large area for installing solar panels. Hydrogel-embedded heat exchangers are designed to resolve these issues. The hydrogel materials within these heat exchangers can provide good flexibility and transparency for the buildings, as well as accurate solar-to-heat conversion. The latest advances in these hydrogel-embedded heat exchangers enable the formation of thermochromic devices [95]. Right after fabricating the samples, the experiments began by loading the commercial heat-resistant silicone encapsulant into the container and then squeezing–the four samples to evaporate the organic solvents. The hydrogel layer and the thermal chart are now clear due to the refractive index match between PDMS and the hydrogel. These cooling systems with strong heating can achieve the potential of a hydrogel-enabled heat exchanger, with good scalability as well [96].

Hydrogel-embedded heat exchangers, which exploit hydrogels' radiative properties to cloak surfaces, transfer heat to a circulating cooling fluid, and substantially lower the temperature of solar cells housed within glass rooms. We propose and demonstrate the hydrogel-embedded heat exchangers as a new thermal cooling strategy for residential solar engineering. With declining solar panel costs and the Earth's commitment to renewable energy, the solar field has taken off with accelerating momentum [97]. However, behind these earthshaking advances, there is an unnoticed inconvenience: insufficient efficiency per person, which squeezes profits in many regions where ultrasonic technology is required. Enhancements are increasingly evident in ~~the~~ congested urban areas where sufficient rooftop space is available.

5.7. Hydrogel-Based Cooling Systems in Concentrated Solar Power Plants

Concentrated solar power (CSP) plants are renewable energy sources that have diversified the market by increasing electricity generation efficiency. CSP plants operate by concentrating solar energy using mirrors and/or lenses on an absorption medium to convert the light into heat. The generated heat can reach temperatures above 500 °C, and the system operates a cooling cycle to generate electrical energy [98]. Nowadays, the most widely used CSP technologies operate on a ranking cycle, heating a heat-transfer fluid. The heat is converted into thermal energy.

The majority of CSP technologies use water as a heat-transfer fluid; however, the number of Generation IV CSP technologies using molten salts is increasing. Polymer-based materials that operate efficiently at high service temperatures are promising candidates for the manufacture of heat exchangers, reactors, etc., suggesting that increased research investment in this field is expected [99]. Therefore, given hydrogels high-performance capacity to remove high heat fluxes and maintain their mechanical stability at high service temperatures, hydrogel technology could represent a promising alternative, thereby contributing to efforts to maximize the efficient operation of CSP technologies. This section reviews the use of hydrogel-based cooling technologies in CSP plants. The factors that affect heat-transfer performance and limitations are analyzed, and the implications of the current state of the art are evaluated [100]. The section closes with an appealing conclusion and a discussion of performance and thermal management advances.

5.8. Hydrogel-Based Cooling Technologies for Portable Solar Panels

The use of solar panels for personal energy generation, i.e., portable solar panels, has expanded into niche applications beyond general deployment in power plants or on building rooftops. The majority of solar panels were used either as portable chargers or as backpacks. They are typically used to charge electronic devices like mobile phones, tablets, or laptops, and some are even designed to charge the built-in battery while powering the device. However, to design and manufacture efficient portable solar panels, the major challenge of heat dissipation must be addressed.

This work, discusses various developments in the application of hydrogels in portable solar panels. In general, integrating hydrogels can enhance the heat dissipation of solar panels with minimal interference with power generation efficiency [101]. Additionally, the use of porous flexible substrates in the design of hydrogel-coated solar panels not only helps maintain a lightweight, slim design but also enables wearability, thereby adding value to portable solar panels. Overall, hydrogels are shown to be a versatile material for addressing heat dissipation issues in portable solar panels and as an attractive candidate for flexible and wearable technologies.

6. Challenges and Limitations in Solar Panel Cooling

Converting solar energy into electrical power is one of the most efficient ways to step up solar power generation. Theoretical upper limits for solar cell conversion efficiency are 86–94% with multi-junction cells. As a consequence of the photovoltaic effect, solar panels dissipate and no longer convert about 75% of the solar energy they harvest on average. This leads to temperature increases and reduced electrical performance. Solar panels are typically coated with a glass layer, an anti-reflective coating, and encapsulated with UV-blocking polymer layers, and backed with aluminum to protect the solar cells from environmental damage and to minimize heat loss [102]. These layers also work as thermal insulators, preventing heat from dissipating into the environment. High operating temperatures also lead to yellowing of encapsulations, a decrease in luminescent transmittance and a 10–20% reduction in electrical efficiency from harvested light.

Bonders have been developed with significant effort to broaden the absorption spectrum and improve the photon-to-electron efficiency. In any case, the electrical performance of solar panels still rapidly decreases at high temperatures. Effective cooling of solar panels is key to ensuring optimal efficiency and extended lifespans. Several cooling technologies have been proposed and tested, including mirror concentrators, adding evacuated tube coolants, immersing solar panels in saltwater pools, incorporating phase change materials, and spraying microencapsulated water [103]. These cooling technologies yielded almost 85% electrical efficiency at an ambient temperature of 25 °C, but their reliability and lifespan were drained by the experience with water as a major manufacturing quencher for solar panels and by the limited thermal conductivity of the used cooling materials.

6.1. Advantages and Limitations of Hydrogel-Based Cooling Technologies

Hydrogel-based cooling technologies are promising candidates for reducing the operating temperature of photovoltaic panels, thereby extending their lifetime and efficiency. Different strategies can be employed to absorb solar radiation, promote the evaporation of an external water flow, and reduce its heating effect. While a substantial body of literature exists on superabsorbent and super-swelling hydrogels for personal comfort applications, only a few studies focus on hydrogel-based cooling systems for solar panels. A comprehensive, detailed description of hydrogel-based cooling technologies for the thermal management of photovoltaic solar panels is proposed [104]. This review is intended for readers of all levels, from junior students to research experts. In particular, technical and engineering notes, as well as heating and cooling analyses developed to achieve the thermal control of solar cells, modules, or panels, are critically reviewed.

The temperature of solar panels is lower in winter; indeed, the efficiency of the photovoltaic module can decrease or increase when the temperature is below or above 25 °C, respectively. This fact is known and is verified from the I-V curves of the solar panel. The normal working temperature of crystalline silicon panels used in outdoor applications (35-50 °C) does not differ from that of organic solar cells [105]. This temperature threshold does not depend on the solar panel technology. It is important to cool solar cells, modules, or panels during severe hot conditions to preserve and extend their lifetimes, guarantee the reliability of the output power, and maintain photogeneration of electron-hole pairs. Air conditioning and ventilation systems have high energy consumption; to avoid this, downstream strategies propose different technologies to cool solar panels [106].

7. Future Research Directions

The past two decades have seen growing interest in developing hydrogel-based cooling technologies for various solar devices, as hydrogel's boiling heat transfer mode can achieve high heat dissipation rates without consuming significant volumes of cooling water. This review presents state-of-the-art hydrogel-based evaporative cooling technologies, focusing on thermal management and performance enhancement strategies [107]. The scope of the work includes features and cooling mechanisms of hydrogels, critical technologies for hydrogel-based solar cooling systems, and hydrogel synthesis and fabrication technologies. Both efforts should build on the milestones established in the field, but a few major milestones are suggested to guide development of to these critical technologies and systems that incorporate them. Given its desirable wettability and thermal stability, as well as its ease of production and low cost, hydrogel-based solar cooling technology will have a promising future as a commercial product. The current challenge for hydrogel-based solar cooling lies not only in the low evaporation rate and in the optimization of heat transfer augmentation techniques in steady-state working conditions, but also in improving the initial state of low equilibrium hydrogel swelling [108]. This work provides a comprehensive review of the latest strategies and performance improvement efforts to facilitate future research on promising hydrogel cooling technology for solar energy applications.

8. Emerging Research Directions in Hydrogel Cooling for Solar Panels

Hydrogel cooling is designed for cost-saving, environmentally friendly, and efficient solar panel temperature management. Additionally, it has the potential to be deployed in concentrator photovoltaic applications that involve high solar concentration. Within the field of hydrogel cooling research several interesting development avenues remain unexplored for solar panel cooling. The replication of block copolymer structures can enable properties such as thermal conductivity by incorporating unnatural ions available in the solution, which become irreversible in the hydrogel matrix [109]. It is still unclear how the energy from hydrogel cooling affects the performance of solar panels.

The parasitic energy requirements for water transfer, pumps, and overall cooling must be evaluated, and mitigation strategies such as a solar-assisted pump should be proposed. Alternative hydrogels need to be developed and tested to identify materials that are more compatible with the surrounding material of solar panels. As non-conductive hydrogels are the least aggressive toward solar panel materials, they need to be better studied and integrated into cooling designs [110]. High-speed localized evaporative cooling can be introduced to guide the freezing direction, thereby boosting the power [111]. Furthermore, electric-field manipulation or mechanical/geometric boundary manipulation may enhance freezing performance and facilitate natural frequency regulation when multiple cooling pads are deployed for solar panel cooling.

Table 3. Criterion Absorbent Material Cooling for Solar Panel

Criterion	Absorbent material cooling	Heat pipes	PCM (encapsulated)	Water cooling (active)
Thermal performance (typical behavior)	Good at short-term surface cooling, especially via evaporation — can lower cell temp several °C under dry conditions; performance falls in high humidity or when dry.	Excellent for moving the heat from module to heat the sink; maintains lower operating temperatures when a good sink is available.	Effective at smoothing temperature spikes (charging/discharging); less effective for continuous high-heat removal.	Best continuous heat removal when properly sized; maintains the lowest steady-state temps.
Response time	Fast (evaporative cooling starts immediately)	Very fast (near-instant conduction)	Moderate (limited by PCM melting/solidification rates)	Fast-to-moderate (pump/reactor dynamics)
Energy penalty	Low (passive) — minor pumping if active refilling	None (passive)	None (passive)	High (pump power, controls)
Water / consumable needs	Requires water recharge / supply (evaporative loss) — key operational cost	None	None (except occasional containment maintenance)	Requires water, possible treatment, leakage risk
Integration into existing panels	Relatively easy as an add-on layer or pouch; needs adhesion and optical consideration	Requires redesign for thermal contact; sometimes retrofitable with an external sink	Needs back-mounted PCM packs or module redesign (adds thickness/weight)	Requires mounting, piping space, and penetrations — significant redesign for retrofit
Weight & packaging	Low–Medium (depends on hydrogel thickness & water load)	Low–Medium (metal pipes add weight)	High (PCMs add mass; significant for rooftops)	High (pipes, fluid, radiators, pump)
Maintenance requirement	Medium — refill, inspect for biofouling, replace degraded hydrogel	Low — mostly none if sealed and not mechanically damaged	Low–Medium — check for leaks, encapsulation integrity	High — pump maintenance, antifreeze, leak repair, water treatment
Durability (UV, cycles)	Medium — UV + repeated swelling/drying reduces lifetime; salts, algae, dust affect behavior	High if manufacturing quality is good; mechanical damage is the main risk	Medium — cycling can cause segregation and reduced enthalpy; encapsulation lifetime varies	Medium — corrosion, pump wear; components replaceable
Cost — capex & opex	Capex low; Opex can be moderate (water & replacement)	Capex medium; Opex low	Capex medium; Opex low	Capex high; Opex high (energy, water, maintenance)
Scalability (utility → rooftop)	Good for distributed rooftop; water provisioning is the main constraint	Good in many scales; best in concentrated PV or where a sink exists	Good for modular units, but adds structural load	Best for centralized arrays or where infrastructure supports fluid loops
Typical failure modes	Drying out, UV/photo-degradation, microbial growth, salt accumulation	Leak / loss of vacuum, wick clogging, mechanical fracture	Leakage, encapsulation rupture, phase-segregation	Pump failure, leaks, freezing, corrosion
Pros (summary)	Low cost, passive, immediate cooling, easy retrofit	Long lifetime, passive, high conductivity	Passive energy buffering, no water needed	Continuous, controllable, highest cooling power
Cons (summary)	Needs water; durability concerns; humidity-sensitive	Requires good sink; integration precision	Added weight & volume; limited continuous removal	High cost & complexity; maintenance heavy

9. Conclusion and Future Prospects

In conclusion, we summarize various hydrogel-based cooling techniques with favorable properties, along with their influences and performance. With superior optical and mechanical properties, advanced methods such as micro to nanoscale structuring, surface patterning, and complex assembly not only deliver better cooling, performance but also reduce the negative effects of electricity consumption and cooling rate for applications in external photovoltaic solar cells. Among various thermal management strategies, conduction-based methods are more suitable for the internal photovoltaic layer due to their low photon-shading loss.

Although the current reported cooling rates of hydrogel-based cooling technologies are less favorable due to low transparency or unreliable duration, available technologies, including water-transforming hydrogels, dual-irradiation-responsive hydrogels, transparent double-sided aerogels, and fiber-embedded hydrogels, together with advanced investigation, could potentially enhance the cooling rate of hydrogel-based technologies.

Table 4. Summarized of review

Study / Author	Cooling Strategy	Mechanism	Performance Enhancement
[112]	Hydrogel-integrated phase change material (PCM)	Latent heat + evaporative cooling	Peak temp ↓ ~18°C; output power ↑ by 10%
[113]	Hydrogel + nanoparticle infusion	Enhanced thermal conductivity + evaporation	Improved long-term cooling; temp ↓ ~14°C
[114]	Double-layer hydrogel (evaporation + insulation)	Surface evaporation + thermal barrier	Efficiency ↑ 6.2%; temp reduction up to 16°C
[115]	Hybrid hydrogel-radiative cooling	Combines evaporation and infrared radiative heat loss	Sustained cooling day and night; ↓ 12.5°C

It is noteworthy that the performance of hydrogel-based cooling technologies is greatly influenced by environmental surroundings, especially relative humidity. A full operating system should be suggested based on the outdoor data of relative humidity in local areas. Also, a system for collecting and recycling water should be introduced to conserve water, especially in arid areas. To make the frequently discussed structures or methods function in a real operating system, further experiments, along with outdoor long-term monitoring, are essential. In addition, the social awareness of eco-friendly and renewable energy, sustainable treatment for a comfortable life, and the aesthetics or appearance of building constructions are becoming increasingly important. Hydrogel-based cooling technologies, which are simple, lightweight, economical, renewable, environment-friendly, and have a wide range of mechanical, electrical, and optical properties, exhibit potential application prospects.

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