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Review

Overview of Recent Solar Photovoltaic Cooling System Approach

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Abstract: In recent years, research communities have shown significant interest in solar energy systems and their cooling. While using cells to generate power, cooling systems are often used for solar cells (SCs) to enhance their efficiency and lifespan. However, during this conversion process, they can generate heat. This heat can affect the performance of solar cells in both advantageous and detrimental ways. Cooling cells and coordinating their use are vital to energy efficiency and longevity, which can help save energy, reduce energy costs, and achieve global emission targets. The primary objective of this review is to provide a thorough and comparative analysis of recent developments in solar cell cooling. In addition, the research discussed here reviews and compares various cooling systems that can be used to improve cell performance, including active cooling and passive cooling. The outcomes reveal that phase-change materials (PCMs) help address critical economic goals, such as reducing the cost of PV degradation, while enhancing the lifespan of solar cells and improving their efficiency, reliability, and quality. Active PCMs offer precise control, while passive PCMs are simpler and more efficient in terms of energy use, but they offer less control over temperature. Moreover, an innovative review of advanced cooling methods is presented, highlighting their potential to improve the efficiency of solar cells.

Keywords: solar energy; water colling; solar photovoltaic; active cooling; passive cooling

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1. Introduction

Today, one of the primary challenges for photovoltaic (PV) systems is overheating caused by intense solar radiation and elevated ambient temperatures [1–4]. To prevent immediate declines in efficiency and long-term harm, it is essential to utilize efficient cooling techniques [5]. Each degree of cooling of a silicon solar cell can increase its power production by 0.4–0.5%. Therefore, achieving additional cooling of a cell by more than 1.5 °C beyond the existing standard module practices in any location could be beneficial. The primary goal of lowering the temperature of PV modules is to increase the energy yield of solar panel systems. Both air- and water-based cooling methods are employed to reduce the operational temperatures of PV modules. Solar cell cooling plays a crucial role in optimizing the performance, reliability, and longevity of solar panel systems. Effective strategies maximize energy production and reduce temperature stress, making solar energy systems more reliable and cost-effective. Researchers have evaluated cooling system techniques and intelligent control systems, focusing on solar cell cooling systems and phase-change materials (PCMs) [6]. Cooling systems are essential for regulating the temperature of PV modules in large installations, and it is crucial that these methods are cost-effective The following paragraph provides some reasons as to why cooling solar cells is necessary.

Solar cells are temperature-sensitive, and their efficiency decreases as the temperature rises. Most solar cell technologies experience a diminution in performance of roughly 0.5% to 0.8% for every 1-degree Celsius rise in temperature. By cooling solar cells, their operating temperature can be lowered, allowing them to maintain higher efficiency. The operational temperature of a PV module affects its electrical effectiveness and power generation, demonstrating a strong correlation between temperature and the power conversion technique. According to the authors of [7], solar cells capture sunlight and transform it into electrical energy. In this conversion process, some of the absorbed energy is altered into heat. In the case that this heat is not dissipated effectively, it can accumulate within the solar cells, leading to increased operating temperatures and reduced efficiency. Cooling solar cells helps dissipate excess heat, preventing performance degradation. In [8], the solar-based refrigeration system was shown to effectively dissipate heat, reducing resistance and enhancing power output by keeping solar cells cooler. Cooler temperatures help reduce resistive losses and allow the solar cells to operate closer to their optimal voltage and current levels, maximizing their electrical generation capacity and the dissipation of energy [9] as heat during peak sunlight, which diminishes the power output and effectiveness of a PV module. High temperatures can accelerate the degradation of solar cell materials, reducing their lifespan. By cooling the solar cells, the overall operating temperature is lowered, reducing the stress on the materials and prolonging their lifespan. Lower operational temperatures additionally augment the long-standing reliability of the solar cells [10]. The photovoltaic industry enhances the efficiency and durability of polymer-based modules through high-speed and high-resolution surface inspection for extended longevity, superior quality, and increased product yield. Concentrated solar power (CSP) systems distillate sunlight by utilizing lenses or mirrors to generate high temperatures. Cooling mechanisms are crucial in these systems to prevent overheating, maintain cell efficiency, and protect the system components [11]. In [12], researchers extensively studied thermal regulation techniques for PV modules, with a particular focus on PCMs for regulating PV system temperature.

The Web of Science portal has published an updated review on PCM technologies, highlighting the increased amount of research in the domain of cooling solar PV systems over the past five years [13]. Figure 1 illustrates the annual number of relevant publications and citations, showcasing the growing importance of this topic among researchers. Last year, the topic peaked, with over 600 articles published. However, in the 2020–2021 period, the publication growth rate decreased, likely due to the COVID-19 pandemic, while citations increased dramatically. Therefore, it is estimated that, by the end of 2024, the number of research publications, as well as citations, will reflect the trends in and importance of this area, indicating future attention from researchers. This trend underscores the resilience and continued relevance of the topic within the scholarly community.

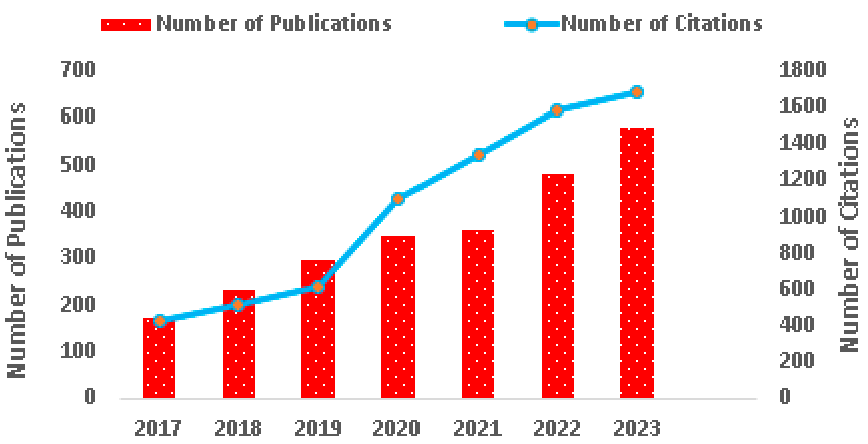

Figure 1. Number of articles in the area of solar cooling published in WOS.

This review is organized into nine sections. Section 1 provides an overview of both solar energy and the cooling systems used to increase efficiency. Section 2 describes the factors that influence the efficiency of solar cells. Section 3 describes an overview of cooling technologies. Section 4 provides an overview of active cooling and a table of the most important studies in the literature that used this system. Section 5 explains passive cooling and provides a table of the most important studies in the literature that used this system. Section 6 provides an overview of the cooling of phase-changing materials and includes a table of the most important studies in the literature that used this system. Section 7 provides an overview of cooling by active phase-changing materials and includes a table of the most important studies in the literature that has used this type. Section 8 provides a comparison of the cooling systems mentioned in this research paper in terms of usefulness, limitations, and impact. Section 9 provides the conclusion and suggestions for future studies. Figure 2 shows the structure of this review paper.

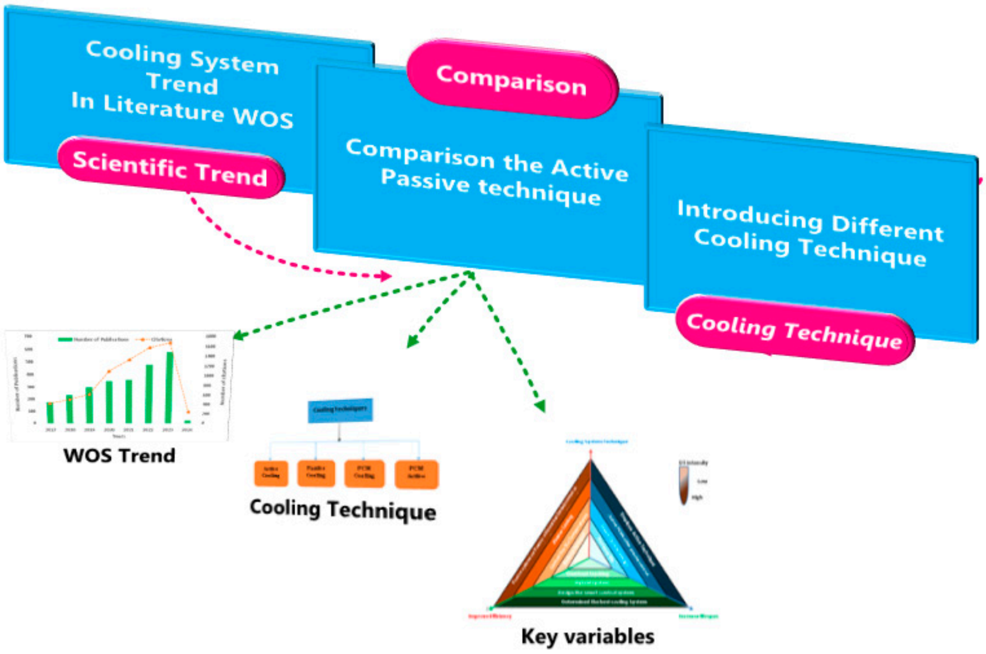

Figure 2. The review paper structure and steps.

2. The Factors Affecting Cooling Performance

Various factors affect the cooling system that enhances the productivity of PV panels, which is essential for maximizing their efficiency and productivity, as presented in Figure 3 [14,15]. Key factors include temperature management, dust, materials, design, environmental challenges, and long-term performance [16,17]. Solar cells are sensitive to temperature changes; higher temperatures can decrease their efficiency, leading to reduced energy generation. The cooling system helps maintain optimal temperatures, thereby enhancing the efficiency and lifespan of the PV panels [18]. Additionally, another important factor affecting the productivity of solar panels is dust accumulation on their surfaces, which can significantly reduce light transmission. The cooling system also aids in the regular cleaning of panels to prevent dust buildup and maintain optimal performance. One of the primary factors influencing cooling system performance is the materials used in its construction. The choice of materials directly impacts the heat transfer rate, durability, and overall effectiveness of the cooling system.

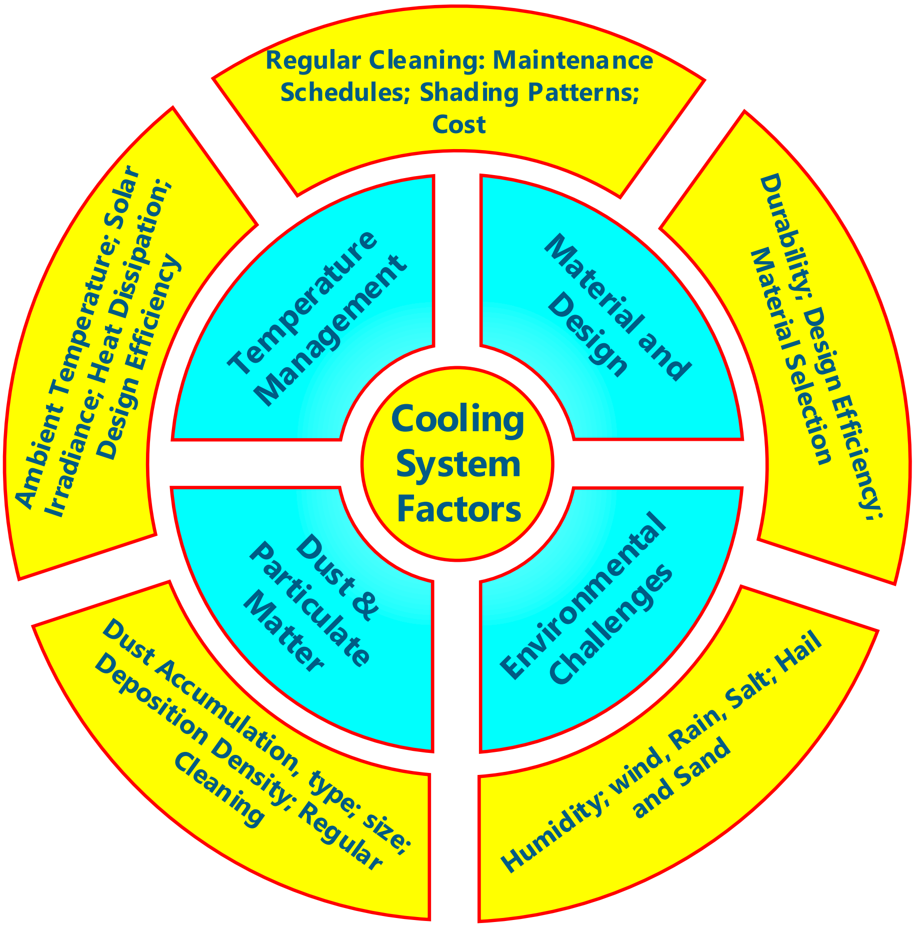

Figure 3. Factors affecting cooling systems.

Long-term performance is another critical factor that must be considered when evaluating the effectiveness of a cooling system. Factors such as material degradation, fouling, and wear can impact the system's efficiency over time. Implementing regular maintenance and monitoring procedures can help mitigate these issues and ensure the long-term reliability of the cooling system. Environmental challenges such as fluctuating temperatures, humidity, wind, rain, hail, sand, and salt can reduce the efficiency and lifespan of PV modules. The cooling system helps in mitigating these effects by maintaining the cleanliness and integrity of the panels. For instance, high humidity can lead to condensation and corrosion, while low humidity can cause overheating. Wind can aid in heat dissipation but also poses challenges in dust accumulation. Rain can clean panels but also lead to temporary drops in performance. Hail and sand can cause physical damage, and salt accumulation in coastal areas can corrode materials [19]. The cooling system must be designed to withstand and adapt to these varied conditions. Figure 3 shows the most common factors that affect cooling performance.

3. Overview of Cooling System Technique

Various cooling techniques can be employed to cool solar cells, including passive cooling methods, such as natural convection and radiation, and active cooling methods, involving the use of a water-spray cooling technique (Figure 4) [20]. Figure 5 shows the immersion of polycrystalline solar cells in water [21]. Figure 6 shows the process of active air cooling [22]. Figure 7 shows the cooling process with PCM [23]. The choice of cooling method is contingent on elements such as the specific solar cell technology, system design, and environmental conditions. In summary, the cooling of solar cells is essential in maintaining their efficiency, preventing performance degradation, increasing power output, extending their lifespan, and ensuring the reliable operation of solar energy systems. Overall, and by reviewing the literature, we can see that water-active cooling systems offer more precise control and higher cooling capacities, making them suitable for applications used in solar cell cooling. Figure 8 shows the most common cooling techniques.

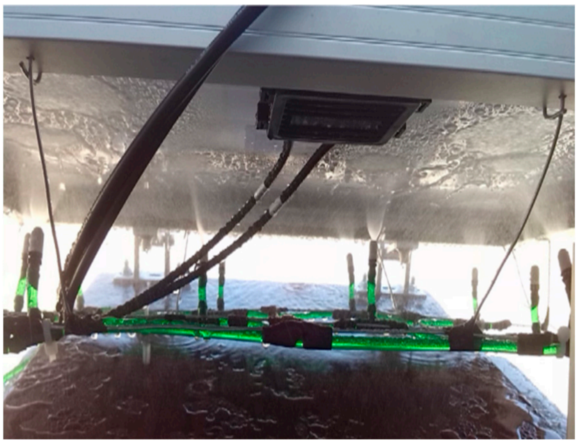

Figure 4. Water-spray cooling technique.

Figure 5. Panel immersed in water.

Figure 6. Air-based cooling technique.

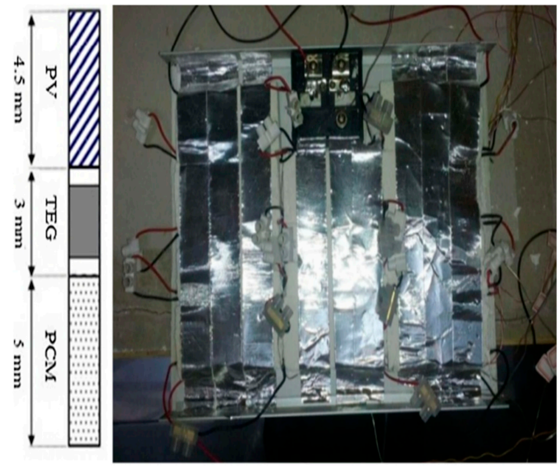

Figure 7. PV/TEG/PCM layout.

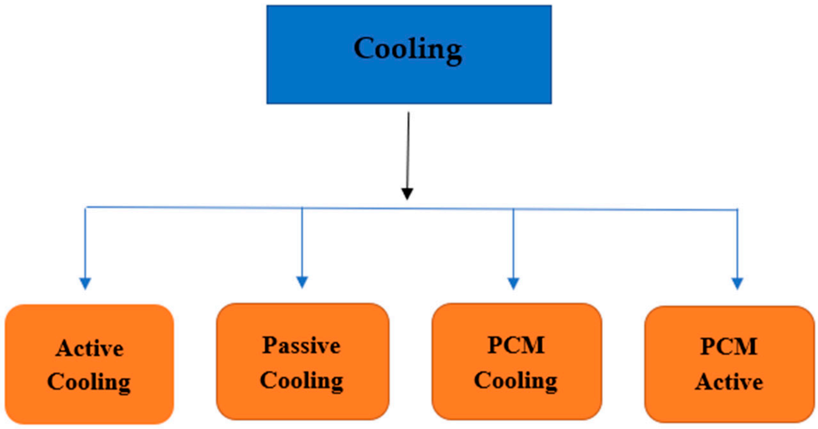

Figure 8. Most common cooling techniques.

The detrimental effect of increasing the surface temperature of PV solar systems, particularly in terms of cooling, is a significant concern for researchers [24]. Passive cooling systems lessen the temperature of PV modules by 6–20 °C, leading to a maximum boost in electrical efficiency of up to 15.5%. Active cooling solutions enhance performance by lowering the temperature of PV modules by up to 30 °C. In [24], the researchers suggested various cooling techniques for photovoltaic panels. The aluminum fins and PCM thermoelectric (TE) were selected for cooling. In [25], the specialists devised a pulsed-spray water cooling system for PV panels that aimed to enhance the efficiency of solar systems while conserving water usage for cooling purposes. The water-spraying approach involves applying a spray of water over the surfaces of PV panels as an alternative method. Another cooling technique involves simultaneously cooling both sides of the PV panel. In [26], the primary performance metrics were detailed for each specific coolant type analyzed, including air, water, and nanofluids. Less-explored cooling methods, namely those associated with concentrated photovoltaic (CPV) systems, have received limited attention. A small number of studies have explored the use of nanofluids in a cooling method for PV systems, highlighting their potential in improving efficiency and longevity.

4. Active Cooling

Active cooling refers to a cooling mechanism that actively removes heat from a system or device. A notable rise in the operating temperature of a cell during the absorption of solar radiation adversely affects its electrical efficiency [27]. Active cooling systems aid in preventing solar cells from reaching elevated operating temperatures, which may poorly affect their performance and efficiency. Active cooling is especially beneficial in regions with high ambient temperatures or in situations where solar panels experience higher heat loads due to factors like concentrated sunlight or limited airflow. It allows for better control and management of the solar cell temperature, ensuring optimal performance and maximizing energy generation. The specific implementation of active cooling methods can vary based on system design, available resources, and cooling requirements. Direct water cooling is a method in which water flows directly over the solar cells' surface, either in contact with the cells or through a separate heat sink. The water absorbs heat from the cells and carries it away, dissipating it through a heat exchanger or a cooling tower.

Another way to active cooling is spray cooling; spray cooling involves the use of nozzles or atomizers which can spray a fine mist or droplets of water onto the solar cell surface. The water droplets evaporate, absorbing heat from the cells and cooling them down. This method provides effective cooling while minimizing water usage. Some researchers have used microchannel cooling; microchannel cooling systems consist of small channels embedded within the solar panel structure. Water flows through these channels, absorbing heat from the solar cells and transferring it away. Microchannel cooling offers high heat transfer efficiency and effective temperature control Others have used heat pipe cooling; here, heat pipes are sealed, closed-loop systems containing a working fluid that transfers heat through evaporation and condensation. Heat pipes are crucial for temperature regulation in solar panels, ensuring efficient heat transfer and the dissipation of heat from cells to the panel structure. To sum up, active cooling is vital for averting overheating and sustaining ideal operational states across various applications. The selection of cooling techniques relies on factors such as device characteristics, efficiency demands, space availability, and cost factors. Table 1 summarizes the findings and details of recent studies in the area of active cooling techniques.

Table 1. Details of several studies on the cooling of PV cells through active cooling techniques.

Year	Referenc	Techniques	Type	Result	Objective
(2019)	[28]	Active cooling	Forced-water cooling; forced-water cooling with buried water	The study demonstrated a 12.20% enhancement in the relative levelized cost of energy as a result of the suggested cooling system. Additionally, this system contributed to a reduction of around 49,209 g CO_2/summer sea in global average CO_2 emissions.	To evaluate the efficiency of a photovoltaic cooling mechanism that combines a V-trough configuration with an underground water heat exchanger.
(2020)	[29]	Active cooling	Forced-water cooling	The results indicated that augmenting the mass flow rate of cooling water has negligible effects. However, under ideal conditions, with a solar irradiance of 1000 W m^{-2}, an ambient temperature of 45 °C, and a water velocity of 0.9 m s^{-1}, the cell's efficiency improved by 17.12%.	To explore how changes in ambient temperature, the flow rate of cooling water, and solar irradiance affect cell efficiency and temperature.
(2017)	[30]	Active cooling	Forced-water cooling	Improves electrical efficiency; yet, with a steady flow rate, it cannot achieve maximal efficiency. If you want maximum efficiency, it is best to modify the flow rate when the temperature changes.	To reduce the negative effects of increased temperature using various techniques.
(2018)	[31]	Active cooling	Forced-water cooling	Experiments were conducted to determine the ideal cooling cycle, which was 20%/80%. The cooling system had an initial startup temperature of 30 °C. We anticipate a two-year payback period for the system.	To cool many photovoltaic chains simultaneously, both on and off, and to consider different facets of its potential as a product for commercial use.
(2020)	[32]	Active cooling	Forced-water cooling	The research demonstrated that the peak exergy of the hybrid renewable system amounts to 872.06 kWh, representing a 2.6% increase compared to the maximum exergy achieved using the Taguchi standard orthogonal array (849.9 kWh).	To maximize the overall exergy, with the integration of an advanced optimization algorithm.
(2012)	[27]	Active cooling	Hybrid photovoltaic/thermal (PV/T)	Solar cell efficiency went up from 12% to 14% as a result of the precipitous drop in temperature.	To connect a series of ducts to the back of the panel, each with its inlet and output manifold to distribute airflow evenly to cool the PV cells efficiently.
(2017)	[33]	Active cooling	Thermoelectric module (TEM)	Research indicated that the temperature of photovoltaic panels decreased by 6–26% when a temperature-based "Maximum Power Point Tracking (MPPT)" controller was employed under solar insolation levels ranging from 0.8 to 1 kW/m^2 and temperatures between 25 and 45 °C.	To improve the effectiveness and durability of photovoltaic systems. By utilizing thermoelectric technologies to construct and model the PV module
(2020)	[29]	Active cooling	Water flow (forced)	The study revealed that this cooling technique is most efficient in conditions characterized by elevated ambient temperatures and intense sun radiation.	To scrutinize how the mass flow rate of cooling water, ambient room temperature, and variations in solar irradiance affect both the temperature and efficiency of the cell.

Table 1. *Cont.*

Year	Referenc	Techniques	Type	Result	Objective
(2016)	[34]	Active cooling	Forced-water heat exchanger	The effectiveness of the PV panel augmented by 57%, going from 7 W to 11 W, and the module temperature decreased by 32%, from 50 °C.	To study the cooling impact of the PV panel, a forced water heat exchanger will be incorporated through numerical simulation and experimental investigation.
(2016)	[35]	Active cooling	Water flow (forced), reflectors	The cooling system reduces the working temperature of the PV module to 30–35 °C, resulting in an 18.5% increase in power output for water-cooled CPV and an 8% increase for CPV.	To utilize a technique that focuses on and lowers the temperature of sunlight to enhance the electrical performance of the photovoltaic (PV) module.

5. Passive Cooling

Our thorough examination of the literature showed that most investigated passive cooling solutions incorporate PCM, with air-based and liquid-based methods (such as water, nanofluids, etc.) following closely behind [26]. In [36], passive cooling using an aluminum heat sink was studied to evaluate its effect on silicon solar cell performance. The outcomes exhibited a notable improvement in the efficiency of power conversion, exergy, and energy of the solar cell with this cooling method. In [37], researchers used the design of experiment (DOE) methodology to find the best design parameters for fins, such as height, pitch, thickness, number, and tilt angle. Passive fin heat sinks were evaluated in real-world conditions using their optimal design parameters. In [38], the mechanism of passive cooling was devised to tackle the overheating issue of photovoltaic modules. This system involves the utilization of the capillary action of hessian fabric attached to the rear surface of the module and water evaporation to enhance its performance. Air that is static and air that is ventilated are used to cool the modules that have fins. The authors of [39] introduce an innovative passive cooling method for PV modules harnessing the natural flow of cooling water. The system includes a segmented fin heatsink designed to lower the operational temperature of solar modules while maintaining their efficiency intact. The performance of this heatsink under different wind-attack situations is superior to that of the typical continuous fin profile heatsink design [40]. A proposal was made to enhance passive cooling for a solar module by placing it in a heat sink designed as a finned container. This research used palm wax as a PCM, based on the findings of [41], as it costs significantly less than rival commercial PCMs, it exhibits selective spectral cooling, and because passive radiative cooling relies on the PV module's natural ability to reduce heat [42]. In [43], a novel PV panel passive cooling solution is introduced. A segmented aluminum sheet was suggested as a way of enhancing cooling in high-irradiation environments through enhanced airflow. In [44], passive cooling was implemented by adding perforated aluminum fins to the back of the PV panel, resulting in a synergistic design approach when combined with PV systems. The integration of these technologies not only improves energy efficiency and performance but also contributes to a greener and more resilient energy future. Table 2 summarizes the findings and details of recent studies in the area of passive cooling techniques.

Table 2. Details of several studies on the cooling of PV cells through passive cooling techniques..

Year	Referenc	Techniques	Type	Result	Objective
(2018)	[45]	Passive cooling	Convection or conduction	Passive technology is more advanced than other technologies but requires additional maintenance. Passive technology is more economically efficient when considering the factors that limit it.	To enhance the efficiency of a photovoltaic panel by employing various methods to lower its temperature.
(2021)	[38]	Passive cooling	Cooling by natural water evaporation	An evaporative cooling system helped achieve a substantial 26% drop in temperature. The operational temperature of the reference module fluctuated between 54.2 °C and 76.4 °C, averaging at approximately 66.4 °C.	To scrutinize the efficacy of water-based passive cooling mechanisms in enhancing the efficiency of photovoltaic (PV) modules in hot, arid environments.
(2020)	[39]	Passive cooling	Natural water circulation	The introduction of nano-composed oil resulted in the greatest augmentation of the maximum generated power compared to the reference condition. The percentage enhancements were 44.74%, 46.63%, and 48.23% at radiation intensities of 410, 530, and 690 W/m^2, respectively.	To insert nano-composed oil to increase the maximum generated power compared to the baseline condition. The percentage improvements were 44.74%, 46.63%, and 48.23% at radiation intensities of 410, 530, and 690 W/m^2, respectively.
(2022)	[46]	Passive cooling	Floating photovoltaic system	The research demonstrated that the improved floating PV system featuring a finned heatsink outperforms the conventional floating photovoltaic system, decreasing the operating temperature by roughly 19.07%.	To improve the efficacy of a floating PV system, a novel partially floating system is combined with a passive arrangement of finned heatsinks to lower the operating temperature and sustain the module's productivity.
(2019)	[47]	Passive cooling	Evaporative cooling and natural water mass	Raising the water mass from 0 kg to 600 kg (heat capacity) leads to a 4.67% increase in electrical efficiency, attributed to a 4.79 °C decrease in solar cell temperature at midday.	To comprehend the impacts of different passive cooling methods on integrated semitransparent photovoltaic thermal systems.
(2014)	[48]	Passive cooling	Rainwater, gas expansion device	On a design day, the research indicates a reduction in cell temperature along with an 8.3% upsurge in the electrical efficiency of the PV panel attributed to the passive cooling system.	To employ rainwater for passive cooling in a solar system to enhance its performance by distributing it through a gas expansion mechanism.
(2021)	[36]	Passive cooling	Plant cooling, greenhouse cooling, coir pith	Examples of net cooling within greenhouses and cooling plants using greenhouse structures demonstrate that temperature reduction does not consistently lead to increased power. Nations in tropical regions with agriculture-based economies stand to gain the most from employing this cooling technique.	To measure a 50 W polycrystalline photovoltaic module's power generation and temperature drop.
(2011)	[49]	Passive cooling	Aluminum heat sink	Under conditions of 800 W/m^2 radiation, the PV cell's power production increases by around 20%. The cooling effect is most pronounced at an intensity level of 600 W/m^2. Photovoltaic cell efficiency increases when temperature decreases, regardless of the presence of fins.	To understand how passive cooling with an aluminum heat sink affects the performance of silicon photovoltaic systems under various radiation settings.

Table 2. *Cont.*

Year	Referenc	Techniques	Type	Result	Objective
(2013)	[37]	Passive cooling	Cotton wick	A 30% enhanced cooling system has a 1.4% increase in module efficiency, resulting in a 15.61% increase in PV module output power and a module temperature.	To propose a passive cooling system for flat PV modules using cotton wick structures.
(2021)	[50]	Passive cooling	Fin heat sinks namely	The payback period for different types of PV modules was determined to be 4.2 years for longitudinal fins, 5 years for lapping fins, and 8.4 years for exposed PV modules. The electrical efficiency and power output achieved were 10.	To evaluate the efficiency of passive cooling in a concentrated solar module experimentally by using two different types of passive fin heat sinks: pounding and long-term.
(2020)	[51]	Passive cooling	Lapping fin, wind speed	Increasing the fin pitch from 20 to 60 mm reduced the number of fins from 20 to 10 and raised the PV module temperature from 44.13 to 54.01 °C.	To improve the efficiency of the PV module, they incorporated a planar reflector and expand the surface of the back plate.
(2021)	[38]	Passive cooling	Heat sink, aluminum fins, ultrasonic humidifier	The study employed a cooling technique that reduced the temperature of the panel by an average of 14.61 °C. This lessening resulted in a 6.8% upgrade in the electrical efficiency of the module.	To improve the electrical output of the photovoltaic module by employing an aluminum fin heat sink and an ultrasonic humidifier.
(2021)	[52]	Passive cooling	Water evaporation, capillary action, and burlap fabric	The research demonstrated that the proposed evaporative cooling system efficiently lessened the temperature of the PV module by 20 degrees Celsius, marking a 26% reduction. Consequently, there was a significant 14.7% increase in electricity efficiency.	To create a passive cooling system aimed at averting overheating of solar modules while enhancing their efficiency.

6. Passive PCM Cooling System

Recently, there has been a significant increase in the installed capacity of solar photovoltaic cells, particularly crystal silicon cells. Research has focused on enhancing the photovoltaic (PV) conversion efficiency of the cells by exploring methods to cool PV systems, as elevated PV temperatures can reduce conversion efficiency. The efficiency of cooling photovoltaic cells relies on phase-change materials (PCMs) with high latent heat capacities [23]. In fact, PCMs are being studied as a solution for reducing the surface temperature of PV cells during sunlight exposure, with a goal of improving the electrical efficiency of the cells. PCMs can control temperatures by absorbing and releasing thermal energy when they change from one phase to another. This allows them to act as a thermal buffer, maintaining a stable temperature within a desired range. PCM cooling effectively manages heat by absorbing and dissipating excess thermal energy. It acts as a heat sink, preventing overheating and protecting sensitive components or equipment [53]. PCM cooling improves energy efficiency by stabilizing temperatures and reducing reliance on energy-intensive cooling systems. It leads to lower electricity consumption and operating costs. PCMs are effective in storing and releasing large quantities of latent heat during phase transitions, making them valuable for thermal energy storage. This stored energy can be utilized for either cooling or heating purposes [54]. PCM cooling is environmentally friendly as it reduces reliance on energy-intensive cooling methods, leading to lower greenhouse gas emissions. Additionally, PCMs can be derived from renewable or bio-based sources, making them a sustainable cooling option. Figure 9a [55] and Figure 9b [56] show some uses of PCMs. Table 3 summarizes the findings and details of recent studies in the area of PCM cooling techniques.

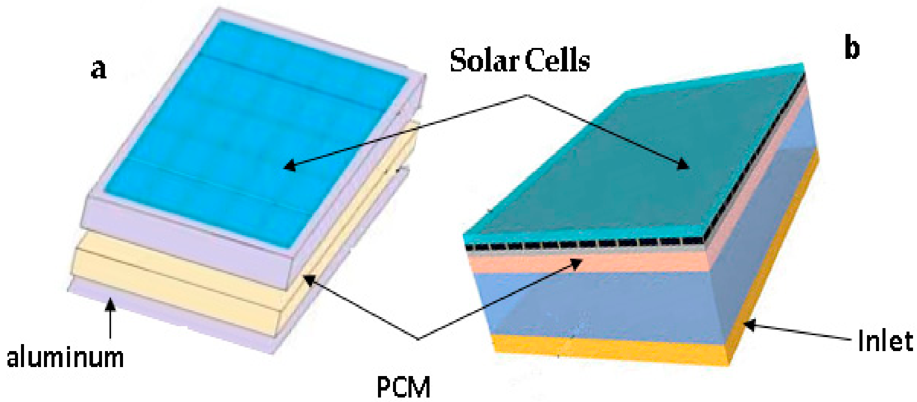

Figure 9. Three-dimensional illustration of PV/PCM configurations featuring aluminum (**a**); schematic representation of an air-based PV/T collector incorporating PCM (**b**).

Table 3. Details of several studies on the cooling of PV cells through composite PCM cooling.

Year	Referenc	Techniques	Type	Result	Objective
(2016)	103	PCM cooling	PV/CS6P-M, PCM	The simulation's final results indicate that the power generation of the PV–PCM panel in Ljubljana exceeded the previous year's output by 7.3%.	To boost the electrical efficiency and power generation of a photovoltaic panel by integrating a phase-change material (PCM).
(2021)	[57]	PCM cooling	PV–PCM cooling systems	The power generated by the PV system rose by 2.5% when utilizing a full PCM container in contrast to a typical PV panel. The innovative PV–PCM passive cooling technology, featuring numerous dissimilar PCM containers, elevated performance by 10.7% compared to the use of a solitary PCM container.	To review the traditional passive cooling method frequently utilized in photovoltaic systems by integrating phase-change material for cooling (PV–PCM cooling systems).
(2021)	[58]	PCM cooling	Water (natural), nano-PCM, PV	The results indicate that utilizing nano-composed PCMs derives superior results compared with using traditional PCMs. The most notable improvement in maximum power output was observed with nano-composed oil, reaching 44.74%, 46.63%, and 48.23% at radiation intensities of 410, 530, and 690 W/m^2, respectively.	To propose a novel passive cooling arrangement for photovoltaic modules that utilizes natural water flow for cooling, supplemented with a nano-enhanced cooling system.
(2019)	[59]	PCM cooling	PV/T-PCM, nanofluid	Increasing coolant concentration boosted electricity and power generation, while higher nanofluid concentration increased pumping power but decreased thermal–electrical equivalent power.	To measure the thermal and electrical efficiency of a photovoltaic solar panel utilizing a nano-suspension containing multi-walled carbon nanotubes in a water/ethylene glycol (50:50) solution.
(2019)	[60]	PCM cooling	PV, natural water, Al_2O_3/PCM mixture	The results show that including Al_2O_3 nanoparticles at a concentration of γ = 1% enhances the effectiveness of the compound approach (Al_2O_3/PCM combination + water) compared to using 100% water for cooling. The compound strategy using Al_2O_3 (=1%)/PCM mixture (thermal conductivity of PCM = 25%) with 75% water yields the highest photovoltaic performance among all cooling techniques examined.	To implement a compound improvement approach to achieve a cooling effect on PV modules.
(2021)	[61]	PCM cooling	Water/ethylene glycol with PCM	By adjusting the coolant concentration, there was an improvement in electricity and power generation. Similarly, increasing the nanofluid concentration led to higher pumping power but a decrease in thermal–electrical equivalent power.	To assess the thermal of cooling photovoltaic solar panels and electrical efficiency using a combination of multi-walled carbon nanotubes, water/ethylene glycol, and phase-change material.
(2019)	[62]	PCM cooling	PCM, natural water circulation	Incorporating phase-change material (PCM) and using natural water circulation improved the performance of a PV panel. A top-to-bottom continuous water supply cooling method was found to be more effective than previous methods, leading to increased electricity generation.	To evaluate the effectiveness of solar panels in cold climates by employing phase-change material (PCM) with natural water circulation.

Table 3. *Cont.*

Year	Referenc	Techniques	Type	Result	Objective
(2017)	[63]	PCM cooling	Paraffin, PCM, melting range	PCM cooling efficiency decreases in extreme temperatures due to incomplete melting and solidification processes, but in hot climates, the PV–PCM system boosts the annual electrical energy output of the PV system by 5.9%.	To measure the sustained energy-saving efficiency through incorporating paraffin-based PCM with a melting range of 38–43 °C behind the PV plate, while monitoring the cooling effects.
(2023)	[45]	PCM cooling	Nano-emulsions PCM	The mean overall thermal-equivalent energy efficiency reached 84.41%, with a peak of 89.23% when employing nano-emulsion within the module, in contrast to 79.95% and 83.23% observed in the water-cooled system. The collective exergy efficiency stood at 10.69% with nano-emulsion, slightly lower than the 11.66% attained with water.	To evaluate the application of nano-emulsion phase-change materials as advanced coolants to improve the overall efficiency of liquid-cooled PV/thermal systems.
(2022)	[64]	PCM cooling	Foam (AMF), PCM	The PV–PCM/AFM system exhibited lower PV surface temperatures by 4%, 7.4%, and 13.12% compared to standard PV, while achieving higher power outputs by 1.85%, 3.38%, and 4.14%.	To develop a method for passively regulating the temperature of a photovoltaic system using aluminum metal foam and PCM
(2022)	[65]	PCM cooling	PV–PCM cooling, (ECM)	Findings show that PCM can reduce PV temperature by up to 17.5 °C when used as a cooling system, leading to less efficiency losses and more power output. The usage of a 40 mm thick coating of $CaCl_2$-$6H_2O$ boosts the electrical generation for Vicuña by 5.8% and for Calame by 4.5% in a 1-year period.	To upsurge efficiency in silicon photovoltaic (PV) systems, this study compares several PV–PCM cooling system configurations according to PCM material

7. Active PCM Cooling System

The integration of PCMs into photovoltaic (PV) cooling systems has emerged as a promising approach for enhancing the performance and longevity of PV modules. PCMs are substances that absorb and release thermal energy during their phase transition, typically between solid and liquid states, at a specific temperature range. This property makes them ideal for stabilizing the temperature of PV cells by absorbing excess heat during peak sunlight hours and releasing it when the ambient temperature drops [66].

Active PCM cooling systems involve the circulation of a heat transfer fluid (HTF) through a network of channels or pipes that are in thermal contact with the PCM. This active approach ensures that the heat absorbed by the PCM is effectively removed and dissipated, preventing the PV cells from overheating. The result is a significant reduction in the PV module temperature (TPV), which has a direct positive impact on the electrical efficiency of the PV cells [67]. The benefits of active PCM cooling are multifaceted. Firstly, by keeping the PV cells at a lower temperature, the systems can mitigate the inherent decrease in conversion efficiency that occurs as PV cells heat up. This is particularly beneficial in regions with high solar irradiance and ambient temperatures, where the efficiency of PV modules can be significantly compromised.

Moreover, active PCM cooling can extend the operational life of PV modules. High temperatures can lead to accelerated aging and degradation of the module components, including the encapsulant, back sheet, and even the solar cells themselves. By reducing the thermal stress on these components, PCM cooling can delay the onset of degradation mechanisms such as potential-induced degradation (PID), hot spot formation, and corrosion, thereby enhancing the reliability and durability of the PV system [68]. The economic implications of PCM cooling are also noteworthy. By improving the efficiency and longevity of PV modules, active PCM cooling systems can contribute to a higher return on investment for PV system owners. The initial cost of installing such cooling systems can be offset by the increased power output over the lifetime of the PV system, making it an attractive option for both residential and commercial applications. In addition to these advantages, active PCM cooling systems can contribute to the overall sustainability of PV technology. By reducing the energy losses associated with overheating, these systems can help to maximize the energy yield from renewable sources, aligning with global efforts to reduce carbon emissions and combat climate change [68]. As the PV industry continues to evolve, the development of advanced PCM cooling solutions is likely to play a crucial role in the optimization of PV system performance. Ongoing research is focused on improving the thermal conductivity of PCMs, enhancing their heat exchange properties, and integrating them more seamlessly into PV module designs. The ultimate goal is to create a synergistic cooling system that not only protects the PV cells from thermal stress but also contributes to the aesthetic and structural integrity of the PV installation.

In conclusion, active PCM cooling systems represent a significant advancement in the thermal management of PV modules. By effectively reducing TPV and enhancing performance, these systems are poised to become an integral part of the next generation of PV technologies, driving the industry towards higher efficiency, greater reliability, and increased sustainability. Figure 10 represents one of the types of active PCM cooling [69]. Table 4 shows the most common studies in this area.

Table 4. Details of several studies on the cooling of PV cells through composite phase-change material (PCM) systems.

Year	Referenc	Techniques	Type	Result	Objective
(2022)	[70]	PCM active	PV–PCM-TE system	Research findings show that in a PV–PCM-TE system, solar cells cooled from 79.72 °C to 57.39 °C, while in a PV-TE system, the temperature remained at 73.62 °C. The yearly average efficiencies were 17.57% for PVs.	To boost power output through the optimization of thermoelectric (TE) module attachment and phase-change material (PCM) to photovoltaic (PV) cells.
(2022)	[71]	PCM active	Nano-PCM, PV	Using nano-PCM resulted in augmented electrical efficiency and lower panel surface temperature	To expand the productivity of photovoltaic panels by utilizing nano-phase-change material (nano-PCM) to enhance heat radiation absorption.
(2021)	[39]	PCM active	PCM, nanoparticle	The results indicate that incorporating twisted bundles of multi-walled carbon nanotubes (MWCNTs) into the PCM/CFM at a concentration ratio of 0.2% significantly improved the material's heat absorption and rejection capabilities. Throughout the test, the solar panel's average electrical efficiency surged from 4% to 21% owing to the enhanced electrical performance of the cells.	To examine how empirically dispersing nanoparticles within porous materials and phase-change materials (PCMs) affects the electrical efficiency of photovoltaic (PV) panels in hot climate conditions.
(2022)	[53]	PCM active	PV–PCM/AMF system	Experimental results show significant temperature decreases in July for PV/PCM-AMF and PV/PCM solar cells, with reductions of 8.1% and 13.4% respectively. In contrast, November had the smallest temperature decreases at 3.8% and 5% for the same cells. The annual exergy and energy productivities of the PV–PCM.	To compare the energy and exergy efficiency of a proposed PV–PCM/AMF system with conventional PV systems and PV–PCM systems without metal foam.
(2018)	[72]	PCM active	CPV/PCM, fins	Studies show that both vertical and horizontal fins improve the thermal efficiency of PCM systems. Vertical fins are especially effective in controlling the temperature of PV cells and exhibit better performance than horizontal fins, particularly under a solar irradiation level of 670 W/m^2.	To implement aluminum fins of varying thicknesses in both horizontal and vertical orientations to enhance heat transfer within the PCM.
(2021)	[73]	PCM active	Convection (PVT/PCM-III)	Experimental findings from existing literature were used to validate the outcomes of a numerical model. After 120 min, the conversion efficiency of PV cells in different setups was recorded, ranging from 16.84% to 18.98%, with an inflow velocity of 3 m/s.	To securitize four solar module configurations to ensure a consistent cell temperature for optimal efficiency: a standard PV module (PVT module) and a traditional module featuring a PCM layer beneath (PVT/PCM-I).
(2021)	[74]	PCM active	Solar simulator, PCM	Studies have shown that PCM composites can reduce PV cell temperature by 6.8% and recuperate electrical efficiency by 14%. Implementing active cooling techniques involved flowing water through a cooling block underneath the PVT system at flow rates varying from 0.3 to 1 liter per minute.	To find out the effects of the effectiveness of active PCM on solar panels/experimental study.

Table 4. *Cont.*

Year	Referenc	Techniques	Type	Result	Objective
(2019)	[75]	PCM active	Nanofluid, PCM	A new technology reduces the average temperature of concentrated photovoltaic (CPV) systems by 60% compared to traditional cooling methods. With specific settings, the cell temperature remains below 78 °C.	To evaluate and improve system efficiency by employing nanofluid as the heat transfer fluid (HTF) in a PCM active cooling system.
(2023)	[76]	PCM active	Coconut husk and paraffin wax (PCM)	The outcomes display that the rear surface temperature of a PV panel can reach 69.02 °C under an irradiance of 752 W/m^2. The cooling effect of PCM reduces this temperature by 12.83% compared to a standard PV panel.	To recover photovoltaic output performance and mitigate thermal stress in PV panels, the implementation of active fog phase-change material (PCM) will be conducted. A comprehensive applied study will assess its effectiveness.

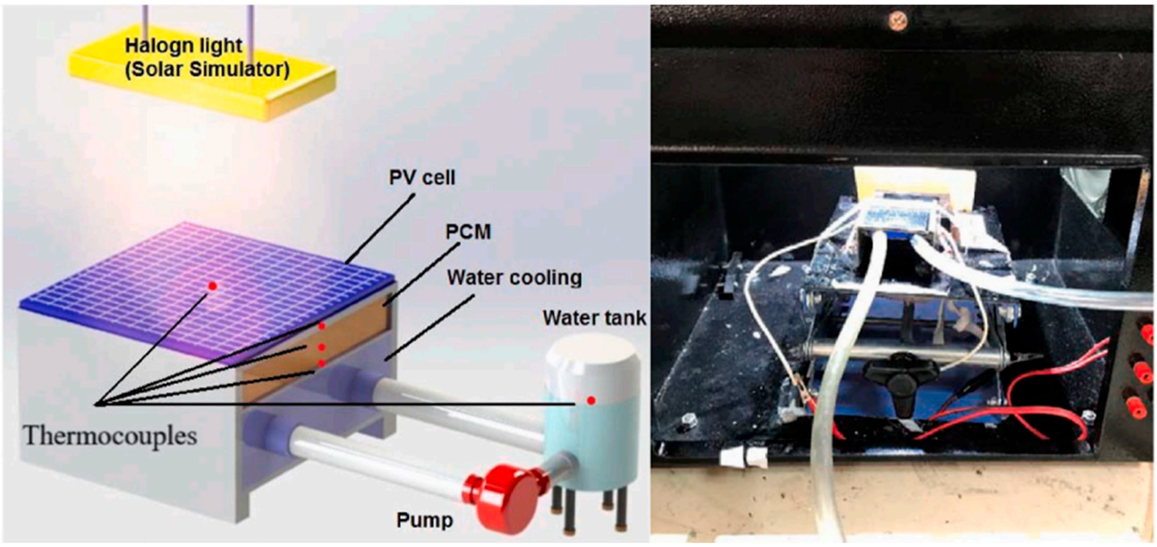

Figure 10. Experimental test facility in PCM active cooling PVT system.

8. Comparison of the Cooling Systems

The comparison of cooling systems in photovoltaic (PV) systems is a critical aspect in undertaking research to enhance the overall efficiency and performance of solar energy conversion. The literature review presented here revealed that cooling methods can significantly affect the temperature regulation of PV modules, which in turn influences their electrical output and longevity. Active cooling techniques, such as those involving water or air circulation, can effectively remove heat from the PV cells, but they often require energy input from pumps or fans, which can offset some of the energy gains. Several cooling techniques are employed for solar PV, and how these technologies impact solar PV is discussed in [61]. In [77], active and passive cooling techniques for a CPV system. In the functioning process, a wide microchannel heat sink (WMCHS) and manifold microchannel heat sink (MMCHS) are used to achieve better thermal management of the CPV system. Passive cooling methods, on the other hand, rely on natural heat transfer processes and do not require external energy input. PCMs are a popular choice for passive cooling as they absorb and release heat during their phase transition, helping to stabilize the temperature of the PV modules. The integration of PCMs with other passive techniques, such as the use of metal fins for heat dissipation, can further enhance the cooling effect. The study of microchannel heat sinks in [77] for concentrated photovoltaic (CPV) systems shows promise due to their ability to efficiently remove heat over a large surface area. The comparison between wide microchannel heat sinks (WMCHSs) and manifold microchannel heat sinks (MMCHS) provides valuable insights into the design considerations for effective thermal management in CPV systems. Moreover, the development of numerical models for proton exchange membrane fuel cells in [78] demonstrates the complexity of thermal management in energy conversion systems. These models can be adapted and applied to PV systems to predict and optimize cooling performance. The experimental investigation in [79] into the cooling of electronic chipsets using both active and passive methods is particularly relevant to PV systems. The findings that the combination of active and passive cooling can significantly improve thermal management are applicable to the design of cooling systems for PV modules.

The impact of operating temperature on the electrical and thermal efficiency of PV panels cannot be overstated. High temperatures can lead to a decrease in power output and accelerated degradation of the PV material. Therefore, research into various cooling methods is essential for the advancement of PV technology. The use of PCMs, as highlighted in [80], is a promising area of research. PCMs can provide a stable temperature environment for PV cells, which is crucial for maintaining high performance. The comparison between systems with and without active PCM cooling in [81] clearly shows the benefits of using active PCMs, such as improved temperature regulation and, consequently, higher energy conversion efficiency. In conclusion, the comparison of cooling systems in photovoltaic systems reveals that there is no one-size-fits-all solution. The choice of cooling method depends on various factors, including the specific type of PV system, the climate in which it is installed, and the balance between cooling efficiency and energy consumption for the cooling process. Ongoing research and development in this area are crucial for the continued improvement of solar PV technologies and their widespread adoption as a sustainable energy source. In summary, the choice between active and passive cooling and active and passive PCMs depends on the specific requirements of a given application. Dynamic systems are suitable for precise control and high heat loads, but they are energy-intensive. Passive systems are more energy-efficient but may have limited control or may not handle extreme conditions well. Active PCMs offer precise control, while passive PCMs are simpler and more efficient in terms of energy use but offer less control over temperature.

Figure 11 shows the variables which are important in designing a cooling system. The figure presents a comprehensive overview of cooling system techniques, structured as a pyramid to illustrate the hierarchy and interrelation of different strategies. At the base of the pyramid, the focus is on improving efficiency through foundational methods such as determining the best cooling system and designing a smart control system. These elements are crucial as they provide the groundwork for more advanced cooling strategies. The integration of hybrid systems and techniques for overheat tracking ensures a balance between passive and active cooling methods, aiming to control temperatures effectively and prevent hotspots.

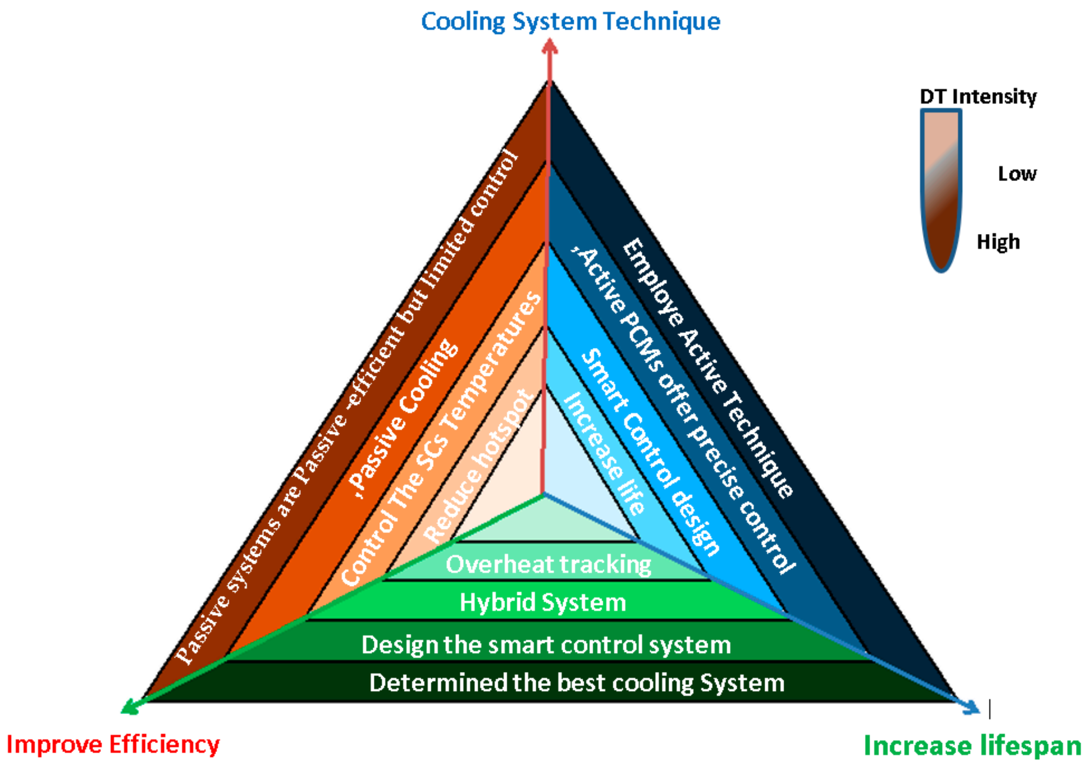

Figure 11. Cooling system strategies.

As we move up the pyramid, the emphasis shifts towards increasing the lifespan of the cooling systems. This involves employing advanced active techniques and smart control designs, which offer precise control over temperature management. The use of PCMs is highlighted for their ability to provide precise thermal regulation. The color gradient from low to high DT intensity underscores the increasing complexity and effectiveness of these methods. Overall, the pyramid visually encapsulates the progression from basic to advanced cooling strategies, emphasizing the importance of both efficiency and longevity in system design.

Table 5 provides a comparative analysis of different cooling techniques for solar PV systems, including both passive and active methods. It delves into the advantages and disadvantages of each technique, shedding light on how these cooling mechanisms impact the overall performance of solar energy systems. Passive cooling, relying on natural heat dissipation, offers simplicity and low cost but may be insufficient in high-temperature environments. Active cooling, on the other hand, utilizes energy to remove heat more effectively, potentially increasing system efficiency, but this comes at the expense of higher operational costs and greater complexity. The table also explores the impact of these techniques on the longevity of PV modules and their environmental footprints, helping to inform decisions on the most suitable cooling approach for various solar energy applications.

Table 5. Comparison of the four cooling systems mentioned in this research paper.

Type	References/ Year	Advantage	Disadvantage	Impact
Active Cooling	[26,82] (2020,2018)	Efficient heat transfer, precise temperature control, suitable for high heat loads, flexibility, higher cooling capacity, adaptability, highly effective in maintaining a specific temperature, suitable for applications where precise temperature control is critical, can handle large heat loads.	High energy consumption, complexity, environmental impact, noise generation, size and space requirements, consumes electricity and can be costly to operate, requires maintenance and can be noisy, may not be ideal for portable or off-grid applications.	Enhanced performance and efficiency heat, dissipation in high-power applications, thermal management in vehicles medical, applications aerospace and space exploration, environmental control in buildings
Passive Cooling	[38,83] (2021,2021)	High effectiveness, energy efficiency, simplicity, reliability, cost-effective, quiet operation, natural ventilation, longevity, suitable for remote or off-grid locations, environmentally friendly.	Slower heat dissipation, limited cooling capacity, lack of precise control, adaptation challenges, insufficient heat dissipation, design complexity, less effective than active cooling for precise temperature control, may not be appropriate for high heat loads or harsh circumstances.	Energy efficiency, cost savings, environmental benefits, low maintenance, resilience, architectural integration, natural ventilation, sustainable design.
PCM Cooling	[84,85] (2023,2023)	Energy-efficient and environmentally friendly, lower operating costs, reduce the average temperature, reduced peak load, thermal inertia, space-efficient design, maintenance reduction, remote and off-grid applications, compatibility with renewable energy, thermal energy storage.	Limited cooling capacity, limited temperature range, thermal cycling fatigue, thermal management, long charging times, volume and weight constraints, thermal conductivity, material compatibility, limited material selection, maintenance complexity, initial cost, limited control over the exact temperature (it stabilizes around the melting/freezing point of the PCM), slower response to temperature changes compared to active systems.	Quiet operation, renewable energy integration, improved thermal comfort, energy efficiency, peak load reduction, temperature regulation, environmental benefits, space efficiency.
PCM Active	[69,86] (2019,2016)	Extract thermal energy stored, thermal energy storage, energy efficiency, temperature regulation, reduced peak loads, thermal stability, space-efficient design, environmental benefits, precise temperature control. Suitable for applications with varying heat loads, can store and release thermal energy efficiently.	Requires energy input for phase change control, complex systems may require maintenance, limited by the specific properties of the pCm used, limited temperature range, thermal conductivity, volume expansion, limited energy density, durability, initial cost, complexity of system, integration, regulatory and safety concerns.	Integration with renewable energy, improved thermal, comfort efficient, thermal storage, energy savings, reduced peak loads, temperature regulation, environmental benefits, space-efficient design.

9. Conclusions and Future Study

In conclusion, this examination of cooling systems in photovoltaic (PV) systems has underscored the importance of effective thermal management in enhancing the efficiency and longevity of solar energy conversion. The literature review has shown that both active and passive cooling methods have their merits and drawbacks. Active systems provide more immediate and controllable cooling at the expense of energy consumption, while passive systems offer a more sustainable and energy-efficient approach, albeit with potentially less cooling capacity. The exploration of microchannel heat sinks and the integration of phase-change materials (PCMs) with other passive techniques have demonstrated innovative strategies for managing heat in PV modules. The development of numerical models for predicting thermal behavior in PV systems has also provided valuable tools for optimizing cooling designs.

As the demand for renewable energy sources continues to grow, further research into PV cooling systems is imperative. Future studies could focus on the following areas: hybridization of cooling methods, combining the strengths of both active and passive systems to achieve optimal thermal management with minimal energy consumption; exploration of new materials for PCMs with improved thermal properties and phase change temperatures more suited to PV applications; environmental impact—conducting a life-cycle analysis of different cooling technologies and assessing their overall sustainability; economic viability, performing cost–benefit analyses, and examining return-on-investment assessments for PV system operators; scalability—addressing the scalability of cooling solutions from small-scale laboratory tests to large-scale commercial PV installations; field studies and long-term performance evaluations—conducting field studies and long-term performance evaluations in various climatic conditions to validate the effectiveness of these cooling technologies in real-world scenarios.

It is important to note that, while currently available research has laid a solid foundation for understanding and improving PV cooling systems, there is still much to be explored. The pursuit of more efficient, sustainable, and cost-effective cooling solutions will be a critical component in the continued evolution of photovoltaic technologies, ensuring their competitiveness in the global energy market. We are committed to continuing this line of research and will be undertaking future studies to address the topics outlined above. Our goal is to contribute to the development of advanced cooling technologies that can significantly enhance the performance and sustainability of photovoltaic systems.

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