IRAQI Academic Scientific Journals

SAMARRA JOURNAL OF ENGINEERING SCIENCE AND RESEARCH

S.J.E.S.R

Review of the impact of cooling techniques on photovoltaic panel efficiency: Developments, effects, and challenges

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Article Information

Received: 23/11/2025

Accepted: 11/1/2026

Keywords:

Solar Cooling Methods, PV Thermal Performance, PV Efficiency Improvement, Photovoltaic Energy Efficiency.

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Abstract

The increasing demand for photovoltaic (PV) solar energy systems has intensified research into improving system performance. High operating temperatures are a primary factor degrading PV cell efficiency, with electrical yield decreasing by approximately 0.3% to 0.5% for every 1°C increase in temperature. This study reviews passive, active, and hybrid cooling technologies to evaluate their effectiveness in enhancing system efficiency. Passive technologies (e.g., Phase Change Materials, natural convection) offer low-maintenance solutions but typically yield moderate temperature reductions of 10–15°C. Active cooling systems (e.g., forced air, water spraying) provide superior heat dissipation but require external power. Hybrid systems, which integrate these mechanisms, demonstrate the highest potential, with studies reporting surface temperature reductions of 18–26°C and electrical efficiency gains exceeding 10%. The review concludes that while hybrid systems offer optimal thermal management, future adoption relies on improving techno-economic viability and integrating intelligent control systems.

1. Introduction

In light of global efforts to control and reduce carbon emissions, renewable energy is a promising solution, and solar energy in particular is more feasible due to the abundance of solar radiation and the adaptability of photovoltaic cells. It has now become an important part of domestic, agricultural, and industrial applications [1]. Despite the advancements in solar cell technology, heat is still a factor affecting the efficiency of photovoltaic cells, leading to a significant decline in electrical energy production. This is due to the properties of semiconductors, which are negatively affected by temperature, leading to a decrease in total energy production [2]. Meanwhile, every 1°C increase in panel temperature leads to a decrease in efficiency ranging from 0.3% to 0.5%, depending on the photovoltaic cell technology and ambient conditions [3].A large group of researchers have focused on solving and treating this problem by developing and improving cooling technologies for solar energy systems. Cooling technologies are broadly categorized into passive, active, and hybrid methods. This paper critically reviews these categories in Section 4, analyzing their operating mechanisms and performance.It has received widespread attention due to its ability to further control heat dissipation and increase the electrical efficiency of photovoltaic solar panels, especially in hot and dry environments. Studies have shown that hybrid systems can reduce the surface temperature of photovoltaic cells by 18-26 degrees Celsius and increase energy production by more than 10% compared to conventional systems [4]. This study will review, discuss, and evaluate the three technologies according to their operating mechanisms, effectiveness, and tolerance to the surrounding environmental conditions. It will also highlight the best solutions for future sustainable energy.

The primary objectives of this study are to:

(1) Comprehensively categorize and evaluate current passive, active, and hybrid cooling techniques.

(2) Compare their performance in terms of temperature reduction and efficiency enhancement.

(3) Identify key challenges and future directions for the cost-effective implementation of PV cooling systems.

2. Photovoltaic solar

The principle of operation of photovoltaic solar cells depends on the extent of the influence of incident solar radiation (the principle of the photoelectric effect), which was first noticed by the scientist Edmund Becquerel, and through his studies he concluded that there are some materials that generate electrical energy when exposed to direct sunlight [5]. This effect was exploited and scientists were able to manufacture solar cells that convert sunlight directly into electrical energy. As shown in Fig. 1, a typical Poly crystalline PV cell has three main layers: a layer of n-type semiconductor material that has an excess of electrons, a layer of p-type material that has a deficit of electrons, and a p-n junction between them. When sunlight enters the cell, it excites electrons in the silicon atoms, freeing them and creating equivalent positive holes. The electrons move towards the direction of the n-type layer, while the holes move to the p-type layer, thereby producing a direct current. Besides being a clean source of energy, solar energy is also one of the drivers of environmental sustainability and economic development. It reduces greenhouse gas emissions and consumption of fossil fuels, while also creating employment opportunities in the renewable energy sector [3].

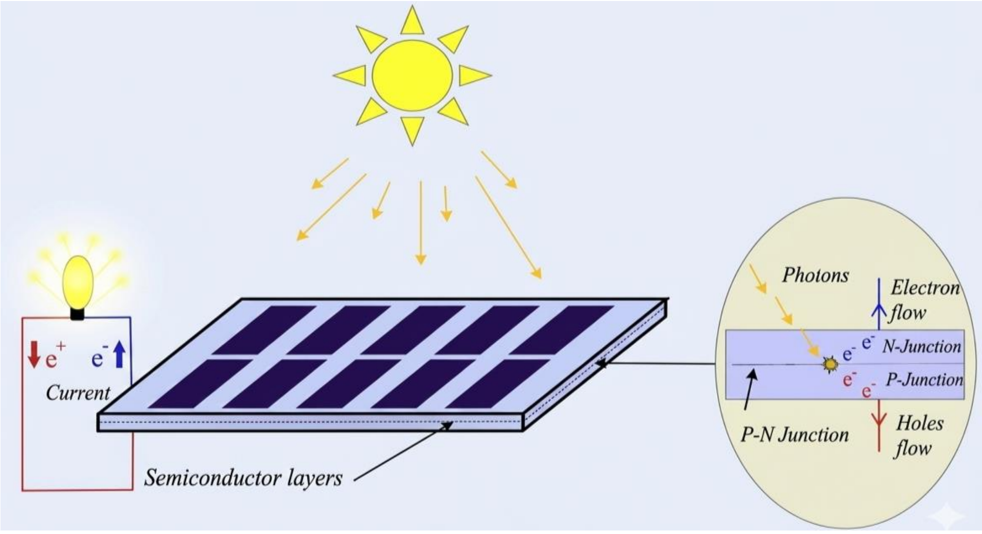

Fig. 1. Fundamental idea behind how a solar cell works [6].

3. Impact of temperature on solar panel efficiency

The performance of photovoltaic (PV) solar panels is highly temperature-dependent, and high operating temperatures result in a considerable loss of performance. The main reason for the decrease in performance is the increase in the electrical resistance of the semiconductor material, which leads to an increase in the amount of losses resulting from the resistance, which leads to a decrease in the power output. The magnitude of this effect is typically quantified by the temperature coefficient of conversion efficiency, which defines the rate at which efficiency decreases with rising temperature. Resistive losses are especially significant because they nearly double as the panel temperature rises from 25 °C to 100 °C [3]. High temperatures, besides resistive losses, also reduce the open-circuit voltage of PV modules, another degradation of their electrical efficiency [7]. These thermal effects affect both voltage characteristics and series resistance, adding up to the overall efficiency reduction [8]. Fig. 2 plots current-voltage (I–V) PV module characteristics at various temperatures under the same solar irradiance of 1000 W/m^2.This thermal problem is particularly disturbing in hot climates, where ambient temperature high and solar radiation high are concurrent. In such an environment, a photovoltaic solar system's efficiency can drastically decline. According to a field test conducted in Benghazi, Libya, the solar panel's surface temperature increased to 71.1°C, 34.7°C above the surrounding air temperature, when the solar radiation intensity was 1017 W/m^2. The primary cause of the decrease in cell efficiency was high temperatures [9]. However, environmental factors like dust and dirt build-up on the panel can also have an impact on cell performance. For Egypt, Cairo, there were thick layers of dust found to greatly reduce the power and efficiency of PV modules, again indicating the multi-dimensionality of degradation under realistic conditions [10].

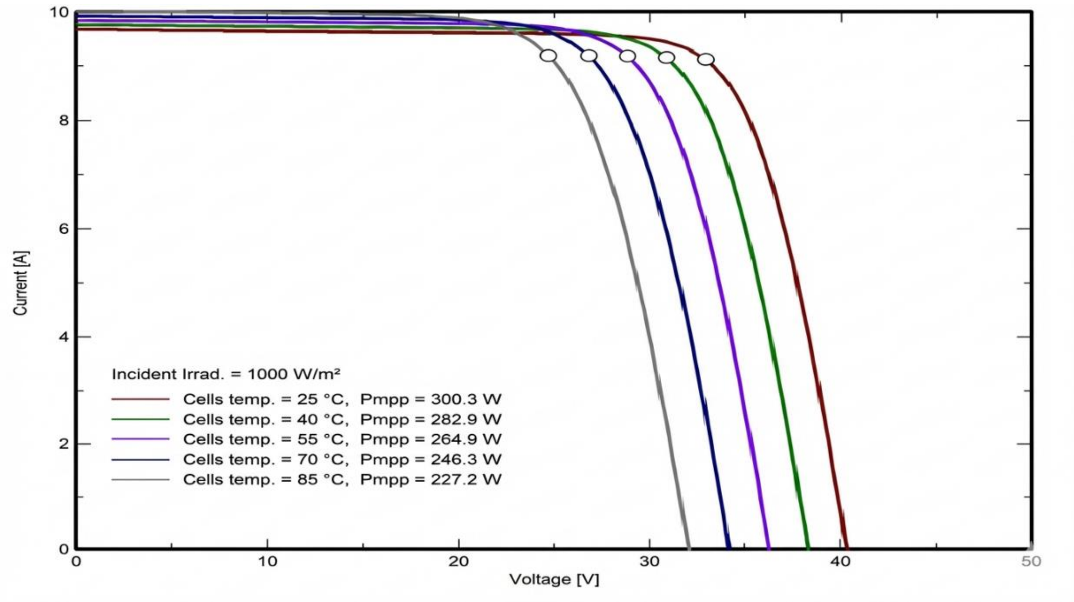

Fig. 2. The impact of temperature on the characteristic curve of solar panels (I-V).

4. Overview of cooling techniques

Operating temperature largely determines the performance and lifespan of photovoltaic (PV) systems. To reduce this, various cooling techniques are utilized that come in categories of passive, active, or hybrid cooling. All these various techniques utilize various mechanisms of releasing heat and hence maintaining solar panels at their best operating temperatures. Thus, the efficiency of electrical conversion is enhanced through these regulatory processes adopted to regulate temperature and maintain the virtual cell life.

4.1 Passive cooling techniques

Passive cooling techniques reduce the temperature of photovoltaic cells, which improves the efficiency and performance of photovoltaic solar panels. They operate without any external power input or active devices. Various passive cooling solutions used in photovoltaic (PV) systems and the extensive research conducted on them are presented in Table 1. They reduce the ill effects of high temperature in photovoltaic panels on system lifespan and electric efficiency, especially under conditions of high sun irradiation. Some of the more important methods are discussed below:

4.1.1 Natural convection

Natural convection is one of the efficient and renewable methods for cooling photovoltaic solar panels. The process is achieved through natural air movement around the panel, as cold air gets denser and sinks whereas hot air gets lighter and rises. Natural convection cools the panels without mechanical or electrical action. Passive cooling forces air movement about the panels to enable heat transfer and improve system performance generally. Natural convection behavior varies depending on several factors such as the panel tilt angle, panel spacing, installation height, wind speed, and ambient temperature. For example, the greater the panel tilt angle, the greater is the mass flow rate and average Nusselt Number. This increases the panel's cooling effect by increasing airflow [11]. Fig. 3 gives a schematic diagram of an inclined air channel with a PV panel mounted above an adiabatic wall. The arrangement features inlet and outlet extensions with provision for airflow movement. The configuration has extensions for the inlet and outlet that allow for airflow. The extensions improve cooling efficiency by increasing mass flow rate and helping to reduce peak temperatures within the channel [12]. Additionally, maximizing heat transfer and lowering panel surface temperature depend on air channel design with the right fin height, thickness, and spacing. It was claimed that cooling performance can be greatly improved by using materials with high thermal conductivity, such as copper fins [13]. The Rayleigh number is another important factor influencing the efficiency of natural convection since it directly affects the air velocity and channel heat transfer rate. It is particularly useful for sloped inlet channels and aluminum flat plate systems [14]. Water surface-float photovoltaic devices have shown that natural convection loops can successfully reduce PV operating temperatures and electrical efficiency [15]. In an industrial context, return air from HVAC systems can also be utilized to improve cooling by generating turbulent airflow, which raises the convection heat transfer coefficient [16]. Transient natural convection behavior is highlighted by research, especially in plate geometries and Rayleigh numbers. It is necessary to closely monitor design parameters in order to achieve a steady-state heat transfer process and optimal cooling effectiveness [17].Temperatures of panels can be minimized to a large extent by structuring PV installations such that there is natural convection provided, which improves efficiency and lowers operation costs and maintenance while proving environmentally friendly [18].By reducing the need for mechanical cooling systems and conserving water in dry and arid environments, the method solves the common issue of PV panel thermal deterioration and enables the sustainable integration of solar technology.

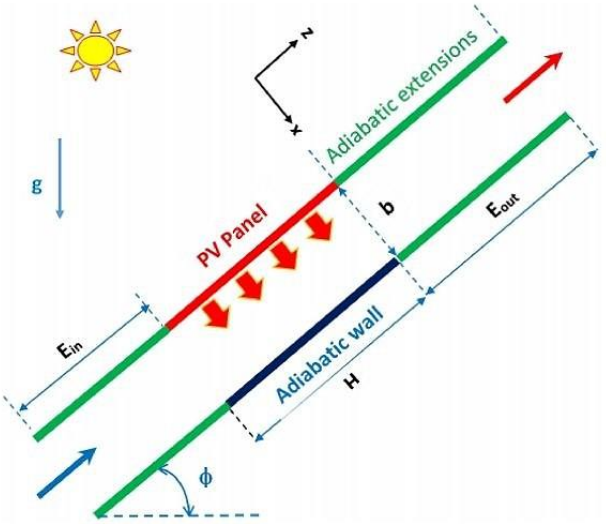

Fig. 3. Diagrammatic Illustration of Adiabatic Channel-Based Passive Natural Convection Cooling for an Inclined Photovoltaic Panel [12].

4.1.2 Phase change materials (PCMs)

Since phase change materials can absorb excess heat during peak hours of sunlight and store it as latent heat, which is gradually released as the temperature decreases, they have been found to be effective in cooling photovoltaic (PV) panels and enhancing their performance. As shown in Fig. 4, the operating mechanism of PCMs incorporated into PV systems. At peak sun periods (left side), the heat generated by the PV cells is captured and stored in the PCM layer, retarding the rise in module temperature. At periods of lower solar irradiance (right side), the stored heat is re-emitted from the PCM, giving a more stable thermal environment to the PV cells. Bidirectional heat flow technology reduces the temperature that causes performance degradation. It also maintains a constant operating temperature by reducing the thermal load on the solar panel, which improves the overall performance of the solar system. Phase change materials (PCMs) are added to solar panels to assist absorb heat, which lowers panel temperature and boosts efficiency, according to earlier research. According to Farhan et al. [19], using soy wax as a PCM to the solar panel's back surface caused a temperature reduction of 18°C.This resulted in a 10.89% increase in power generation. Other passive cooling techniques with good heat dissipation and electrical performance include the use of aluminum fins and other nanoparticles as PCMs [20]. In order to store thermal energy and improve overall system performance, PCMs are utilized not only in photovoltaic systems but also in commercial solar thermal energy systems including solar collectors, solar stills, and solar water heaters [21].Various PCMs including pure PCMs, composite PCMs, finned PCMs, and hybrid PCM systems have been studied for their ability to boost thermal and electrical performance. Pure PCMs such as hydrated salt HS36 and paraffin wax RT42, for example, have shown drastic enhancement, while composite PCMs loaded with multi-walled carbon nanotubes or graphene nanoplatelets have shown certain positive effects on system efficiency [22].

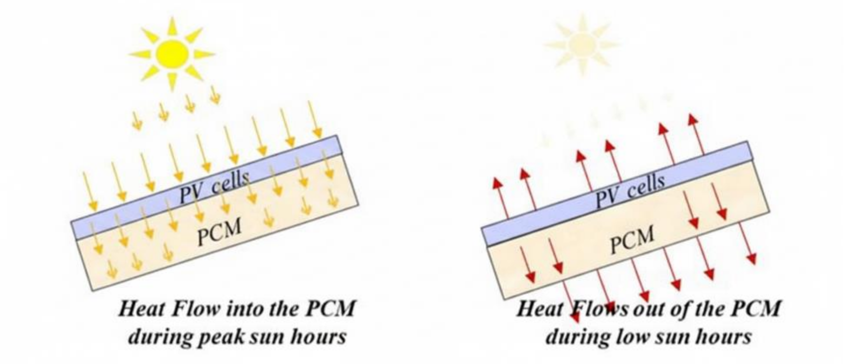

Fig. 4. Phase change materials (PCMs) coupled with photovoltaic panels include a thermal regulating system. Peak sun hours (left) cause heat to be absorbed into the PCM, while low sun hours (right) cause heat to be expelled [23].

4.1.3 Radiative cooling

Radiative cooling is a novel approach used to enhance the thermal performance of solar panels by naturally emitting infrared radiation to reject excess heat to the ambient atmosphere without any external energy input [24]. This process occurs when the amount of radiation emitted from the radiating surface is greater than the amount of radiation received by the surface from the environment. This leads to thermal dissipation, which reduces the operating temperature of the solar panel, as a result, the system's efficiency and electrical energy generation both rise [25]. Fig. 5 illustrates the basic process of radiative cooling by subtracting the absorbed atmospheric radiation from the emitted thermal radiation. The integration aids in improving system performance, producing energy at night, and resolving the present environmental and energy challenges worldwide. Materials that are transparent in the visible spectrum of light but have a high emissivity in the infrared are essential for radiative cooling to work effectively. This dual function is necessary because, in order to prevent thermal degradation, solar panels must simultaneously emit heat and continue to receive sunlight for conversion into electricity. Recent research has suggested complex photonic structures to house this mechanism. For instance, it has been shown that arrays of hexagonal silica microcylinders can enhance infrared emissivity by not inhibiting the transmission of visible light. Zhao et al. [26] presented the use of β-Si_3N_4 dielectric particles suspended in a PVDF matrix with solar reflectivity above 0.91 and atmospheric window emissivity of 0.93. This structure realized a sub-ambient cooling of 11.63 °C in daytime and a theoretical radiative cooling power of 45.41 W/m^2. In another approach, Zeng et al. [27] developed a transparent radiative heat mirror (TRHM) which was fabricated with an indium tin oxide (ITO) layer combined with polydimethylsiloxane (PDMS). This structure allows the passage of visible light while reflecting undesired thermal photons, which resulted in an excellent temperature reduction and improvement of the power conversion efficiency (PCE) of photovoltaic modules. In addition, Li et al. [28] created a novel multilayer prismatic photonic metamaterial film without a silver reflector, with 96.4% sunlight reflectance and 97.2% emissivity in the mid-infrared range. This design worked with an average temperature drop of 6.8 °C below ambient temperature during the day.

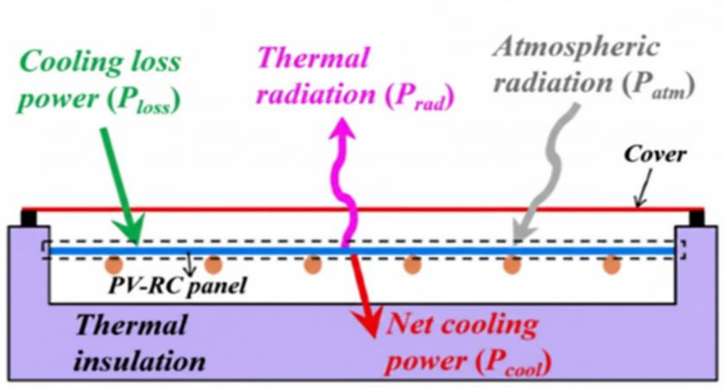

Fig. 5. Diagram of the power balance for radiative cooling [29].

4.1.4 Reflective coatings

Reflective coatings play a critical function to advance the thermal management, efficacy, and lifespan of solar panels, particularly in those regions with intense solar irradiance. They reduce heat absorption by reflecting a fraction of the incoming solar irradiance and hence prevent overheating of photovoltaic (PV) cells. This thermal control is essential because a drop of just 1°C of PV cell temperature may improve energy conversion efficiency by approximately 0.5%.It has been proven through experiments that panels coated with reflective material can show up to a 3% increase in power output compared to uncoated panels, as well as slowing down the long-term degradation of the material. Common reflective materials include aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), and titanium dioxide (TiO_2), which vary from each other in reflectivity, thermal stability, and hardness. As illustrated in Fig. 6, recent reflective coatings such as those containing rutile-phase titanium dioxide blended with ceramic powders have been observed to provide substantial thermal insulation performance when applied on building facades or PV modules. Even greater energy can be saved since these materials not only reflect but also reduce the outer surface temperature. In addition, multilayer reflective structures e.g., passivation films, interface layers, and reflective barriers have been shown to substantially enhance substrate reflectivity, particularly for uses with high temperatures like rapid thermal processing systems [30]. Reflective coatings integrated within photovoltaic modules can enhance spectrum use and UV resistance of the modules [31]. Introduction of reflector geometric details surrounding PV modules has been approximated to increase incidence irradiance by up to 60%, thus increasing permanent thermal efficiency and energy yield [32]. Conversely, reflective mask blanks produced with phase-shifting and reflective films as layers diminish shadowing and light pattern precision even more enhance solar efficiency [33].In rooftop distributed photovoltaic systems, reflective films have been found to lower rooftop surface temperature by 5–25°C, enhance the photoelectric conversion efficiency by 1–6%, and prolong the life of associated electronic equipment [34]. These coatings are usually applied by vacuum deposition or sputtering techniques, and routine maintenance is required in order to achieve their optical and thermal performance.

In summary, decorative reflective panels, such as lattice structure and high-reflectance surfaces, illustrate the extensive application and efficiency of reflective technology in energy systems and architectural applications [35].

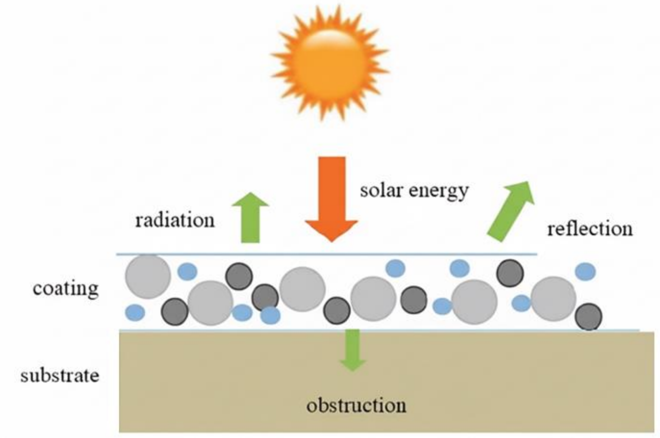

Fig. 6. Diagrammatic representation of the coating-based thermal insulation method [36].

Table 1. An overview of studies on passive cooling methods.

No.	Author	Study	Technique	Temp. Drop	increase Efficiency %	increase Power
1	Genge et al.[37]	Numerical- Investigated effect of fins in chimney-type collector	Passive – wavy fins	14.1 °C	-	-
2	Dida et al.[38]	Experimental-Developed evaporative cooling using burlap cloth	Passive – capillary water action	20 °C	14.75	-
3	Agyekum et al. [39]	Experimental-Dual surface cotton wick cooling	Passive – rear and front side wetting	23.55 °C	11.9	-

4	Horng et al.[40]	Experimental-Used PCM 36 on rear of PV	Passive – PCM cooling	31.67 °C	6.83	-
5	Mohammed Alktraneeand and Peter Bencs [41]	Experimental-Evaporative cooling with cotton wicks	Passive – water absorption	22 °C	53	16.3 w
6	Sachin Prabhakar Badgujar et al.[42]	Experimental-Used paraffin as PCM	Passive – phase change material	11.5 °C	-	-
7	Abdelhafez et al.[43]	Experimental-Applied ZnO + TiO_2 nanofluid	Passive – coated back with nanofluid		29.47	22.81%
8	Mohammad Zuhour et al.[44]	Experimental-Investigated effect of fins for air convection	Passive – rectangular/triangular fins	28 °C	7.3	-
9	Mustapha Salihi et al. [45]	Experimental-Integrated bio-based eutectic PCM	Passive – PCM cooling	11.46 °C	7.23	-
10	Zainal Arifin et al.[46]	Experimental and Numerical- Used soybean wax PCM	Passive – backplate PCM	6 °C	0.42	-
11	Khuram Pervez Amber et al. [47]	Experimental-Compared rectangular vs. circular fins	Passive – rear cooling fins	-	14.5	-
12	G.Hernandez-Perez et al.[48]	Experimental and Numerical- Developed segmented fin heatsinks	Passive – segmented heatsink	7 °C	-	-
13	A. Al Miaari and H.M. Ali [49]	Numerical - Used modular PCM containers	Passive – modular PCM cooling	10 °C	-	5.23%
14	J.Duan [50]	Experimental and Numerical- PCM-porous systems under various inclinations	Passive – PCM with metal foam	11 °C	9	-
15	A. Al-Migdady[51]	Numerical - Integrated porous metal with PCM	Passive – porous heat sink	6.15–7 °C	-	-
16	Z. Arifin et al.[52]	Experimental and Numerical- Compared soy wax, paraffin, beeswax	Passive – PCM types	8.2°C	-	-
17	S.Bhakre et al [53]	Numerical - Water-based PVT/PCM system	Passive – PCM and water tank	23 °C	14.93	-
18	B.Merzah et al. [22]	Numerical - Added Al_2O_3, CuO, ZnO to PCM	Passive – PCM + nanoparticles	-	9.26	-
19	Ahmad et al. [54]	Numerical - Used multi-level fin heat sink	Passive – natural convection fins	-	2.87	-
20	Abdallah et al.[55]	Experimental-Compared four passive techniques	Passive – PCM, fins, ducts	-	72	-
21	Mankani et al.[56]	Numerical - for aluminum air-cooled fins	Passive – air-cooled fin sink	27°C	-	-
22	Moein-Jahromi et al.[57]	Experimental- Nano-enhanced PCM cooling	Passive – GNP/CuO-enhanced PCM	6.6 °C	-	91.81%

4.2 Active cooling techniques

Active cooling techniques are based on mechanical systems where solar panel temperature is reduced through external energy. These techniques are useful in climatically hot environments where passive cooling is not sufficient. Active temperature control of the panel avoids performance degradation, reduces thermal loss, and optimizes energy output during solar radiation conditions, Table (2) presents the most common active cooling techniques.

4.2.1 Air cooling

Air cooling uses mechanical ventilation, i.e., blowers or fans, to actively remove heat from PV panels by enhanced air flow over them. It is particularly suited to sites with temperate ambient temperatures but can be adapted to tropical climates by increased airflow intensity. Although air cooling is generally less effective compared to water cooling since air possesses lower heat capacity, it possesses the advantages of simplicity, cost, and maintenance, and therefore can be a viable option for small scale operation or where water is scarce [58]. Ambient temperature and humidity are the major environmental conditions affecting the performance of air cooling systems. Under hot or extremely humid conditions, the cooling efficiency is lower. However, it has been shown that modern designs that use aerodynamically optimized air channel forms and high thermal conductivity materials (such as copper fins) dramatically improve thermal performance. For example, a case study in Nablus, Palestine, demonstrated that air-cooled channels with well-designed fins greatly reduced the operating temperature of photovoltaic panels, increasing their total efficiency [13]. Fig. 7 illustrates the air-cooling technique, which uses upper and lower ducts through which air passes. This is achieved by sucking in hot air and forcing in cool air, which lowers the panel's temperature. By employing the return air from the air conditioning and refrigeration systems to cool both sides of the photovoltaic solar panel, cooling systems have been designed that have been shown to boost system efficiency by 11% to 18% [16].In these situations, solar-driven air cooling systems are a realistic and environmentally friendly alternative [59]. Because solar powered air conditioners can lower energy consumption, slow down global warming, and enhance indoor air quality, they are regarded as an environmentally beneficial choice. However, in order to minimize climatic factors, design and operation must be optimized [60]. By using some of the refrigerant to cool the solar panels, for example, these combination systems can enhance the system's overall energy [61]. Air conditioning can be a dependable and cost-effective solution despite environmental limitations, especially in rural areas where power and water-based air conditioners are not practicable.

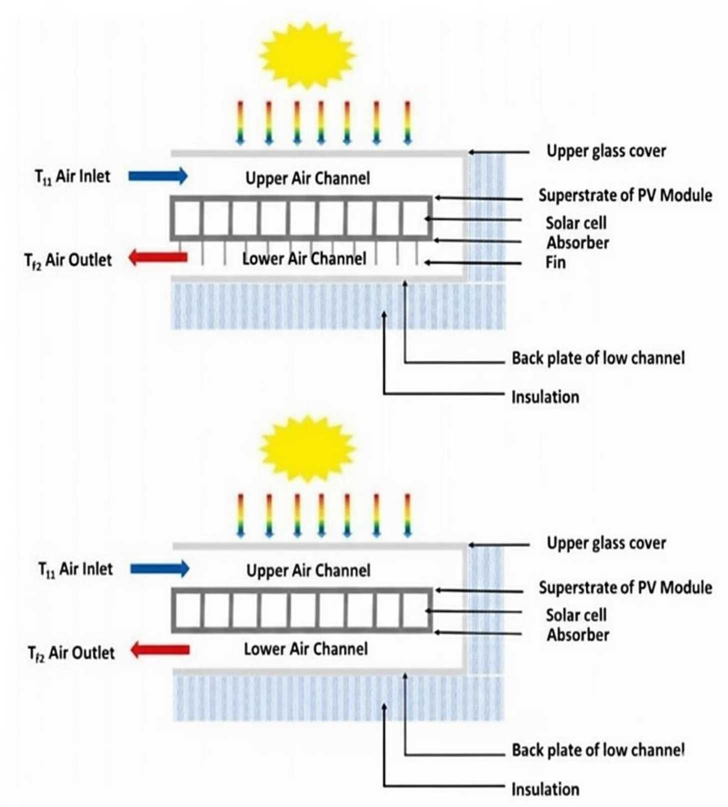

Fig. 7. Cross-sectional side view for convention and improved air channel [62].

4.2.2 Water cooling

Water-cooling techniques have demonstrated superior performance compared to air-cooling systems, primarily due to the higher thermal capacity of water. These methods utilize either chilled or unchilled water as the cooling medium and offer a broader operational range than air cooling, which is generally limited to natural and forced convection. Water-based cooling methods include free and forced convection, front-surface water flow, heat pipe systems, and immersion cooling, as illustrated in Fig. 8.

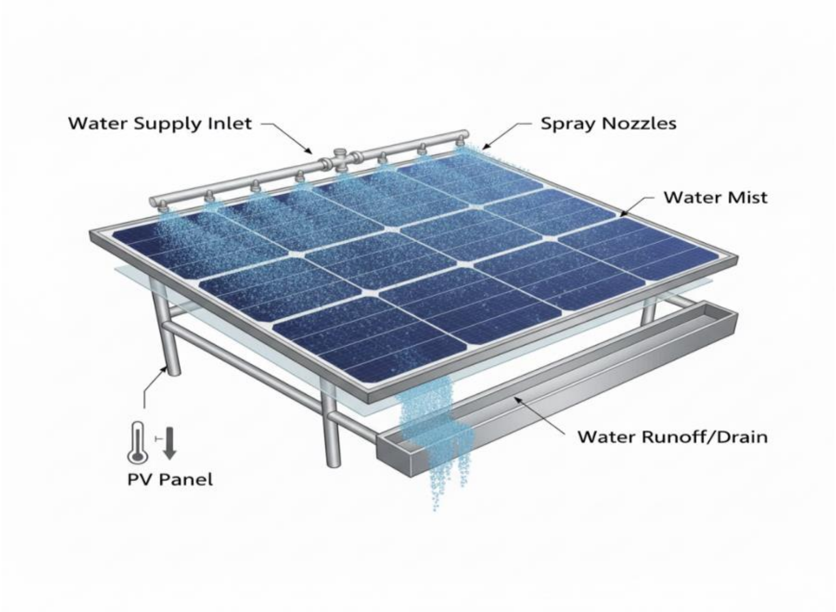

Fig. 8. PV panel with water cooling method [63].

Krauter [64] conducted an experimental study in which water flowed over the front surface of the PV module, resulting in a reduction of optical reflection by 2–3.6% and a temperature drop of up to 22 °C. This led to an electrical efficiency gain of 10.3%, with a net gain of 8–9% after accounting for the pump's energy consumption. Irwan et al. [65] sprayed water on the surface of the PV panel using a direct current (DC) pump and achieved a temperature reduction of approximately 5–23 °C and an electrical output increase between 9–22%.Dorobantu et al. [66] explored front surface continuous water film cooling of PV panels. Their findings showed that there was a reduction of rear surface temperature from 48 °C to 35.5 °C, with a uniform temperature gradient of 7–8 °C across the front and rear surfaces. Yadav and Grubišić [67] compared spray cooling on the front, back, and both sides of PV modules, as shown in the Fig. 9.The electrical efficiency improved by 15.65%, 15.4%, and 15.9%, respectively, with the respective reductions in temperature of 33 °C, 28 °C, and 24 °C.

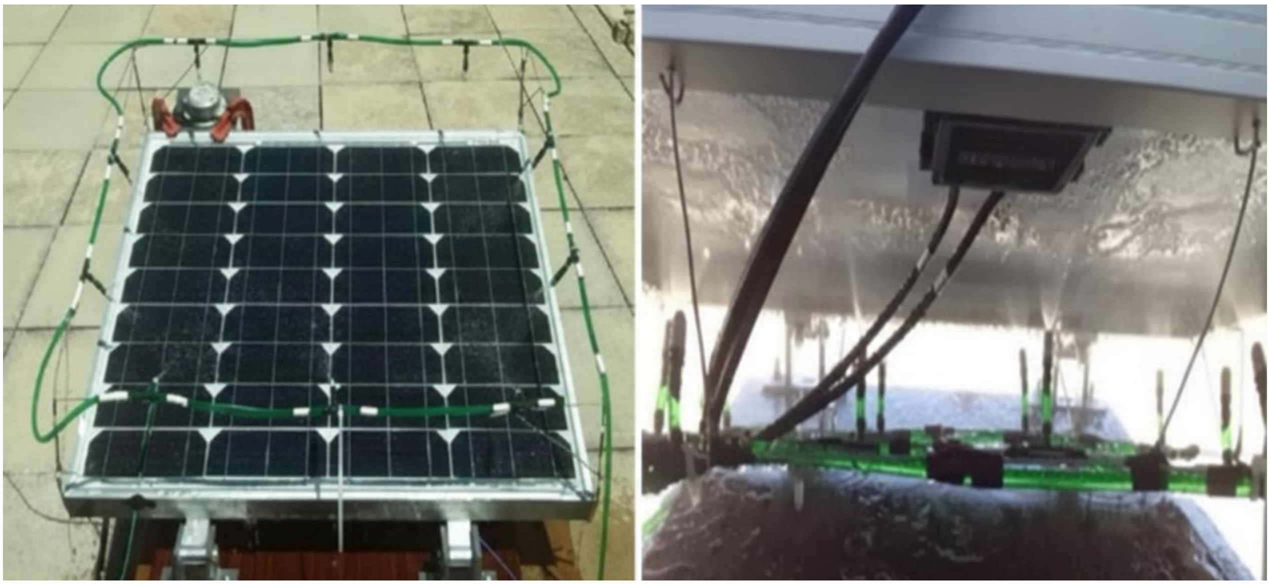

Fig. 9. PV panel with spray cooling system in front and back [67].

Rosa-Clot et al. [68] investigated immersion cooling by submerging PV panels in 4 cm and 40 cm depth water without any structural modification. Our efficiency electric was 14.2% in 4 cm immersion and 13% when it was not cooled and 9.5% when it was immersed at 40 cm. Sun et al. [69] examined the cooling efficiency of immersing solar cells in silicon oil under intense solar flux (9.1 suns) at varying PV module temperatures from 20–31 °C and a fixed conversion efficiency of 13.5%.

4.2.3 Thermoelectric cooling

Thermoelectric cooling, as a result of the Peltier effect, is a new means of temperature control of photovoltaic (PV) panels that involves the generation of a temperature gradient by the flow of electric current between two dissimilar conductors resulting in heat transfer. This technique is particularly beneficial for small or portable solar systems where proper temperature control is important to help maintain performance stability and reliability [70].

Thermoelectric coolers or TECs are tiny, do not have any moving parts, and therefore less maintenance is required but with more reliability compared to other traditional cooling systems [7q]. The operational process of this technology is illustrated in Fig. 10 a typical system integrations consist of a number of layers. Sunlight passes through a covering glass layer before it reaches the PV cells. The generated heat from the cells is channeled to a Tedlar layer, which is an insulating substrate. Below this, a thermoelectric cooler (TEC) module is installed. It is made up of P-type and N-type semiconductor pellets in series, which facilitate the active heat transfer. The TEC's cold side, denoted as Tc, is in contact with the PV module while the hot side, denoted as T_h, is in contact with a heat sink with fins. The fins significantly provide the surface area of heat dissipation into the ambient atmosphere, improving the efficiency of cooling overall. Albeit lower cooling efficiency than with water or air cooling systems, and requiring significant electrical power to function optimally [72], recent improvements in material science have raised their performance to make them increasingly valuable in an increasingly wide range of systems [73].Integration of TECs with PV modules has been found to yield promising results in enhancing solar energy conversion efficiency by maintaining stable operating temperatures, being crucial since PV efficiency decreases with increasing temperature [74]. Experimental work by Mohaimin et al. [72] demonstrated that thermoelectric cooling can increase power output of PV panels up to a level of 5.6%. Yet, energy consumed by the thermoelectric modules can negate such advantages, suggesting their greater suitability in case of small systems or systems with controllers that support optimizing power consumption. Also, double thermoelectric photovoltaic (TE–PV) devices incorporating solar concentrators, PV cells, and thermoelectric generators have been developed to generate electricity from concentrated solar radiation with a maximum power of approximately 1.5 watts in laboratory experiments [75]. Since these must be perfectly balanced to prevent the creation of electrical and thermal resistance, TECs can be further enhanced by employing high Seebeck coefficient thermoelectric materials with reduced thermal conductivity and larger electrical conductivity [76]. Additionally, combining thermoelectric cooling with other renewable energy sources, including earth heat exchangers and solar air/water collectors, can increase system efficiency and broaden the range of applications [77]. One of the most important operation-related issues in solar systems has been resolved by thermoelectric cooling using microcontrollers, which has also been demonstrated to sustain PV panel performance across a range of temperature and irradiance levels [78].

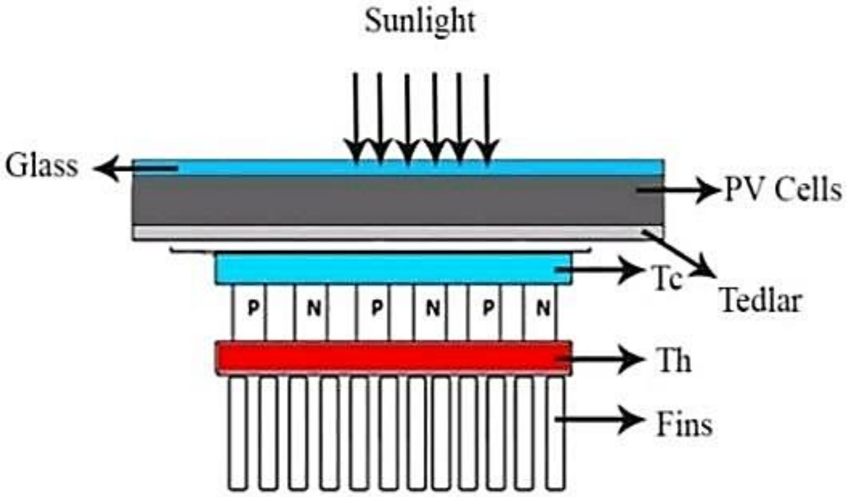

Fig. 10. An illustration showing hybrid PV cells and TEC modules [79].

Table 2. An overview of studies on active cooling methods.

No.	Author	Study	Technique	Temp. Drop	increase Efficiency %	increase Power
1	Malik F. Jaffar et al.[80]	Experimental -PVT system with centrifugal fan	Active – forced air cooling	5–16 °C	-	8.2%
2	Tarek Ibrahim et al.[81]	Experimental -Four prototype configurations	Active – fans and finned plates	-	2.1–3.01	-
3	A. Hussien et al.[82]	Experimental and Numerical	Active – blower and small fans	-	2.1 (fans) ,1.34 (blower)	-
4	Korkut et al.[83]	Experimental and Numerical- PV/T system with PMC laminate	Active – water-cooled hybrid	-	20.8	-
5	Masalha et al.[84]	Experimental and Numerical- Water flow through gravel	Active – porous media cooling	35.7%	-	9.4%
6	Singh et al.[85]	Experimental -Water-cooled copper tube PV	Active – water circulation	15.23%	-	6.08%
7	Farhan et al.[86]	Numerical for Al_2O_3 nanofluid	Active – nanofluid cooling	41–60%	-	-
8	Alqahtani et al.[87]	Experimental and Numerical- Cooling channels optimization	Active – channel geometry	-	0.35	-
9	Setyohandoko et al.[88]	Numerical- model with heat sink	Active – aluminum perforated fins	13.1 °C	0.8	-
10	Faheem et al.[89]	Experimental and Numerical- Hybrid solar thermoelectric system	Active – TECs and TEGs	-	9.54	-
11	Wu et al.[90]	Experimental and Numerical -CPV with thermoelectric cooling	Active – TEC-integrated CPV	39%	-	-
12	Naqvi et al.[91]	Experimental- Mist cooling system	Active – nozzle spray cooling	-	7–9.2	-
13	Abushgair [92]	Experimental- Air-to-air heat exchanger	Active – blower + chimney	40 to 34 °C	-	12.8%
14	Arifin et al.[93]	Experimental and Numerical- with aluminum heat sink	Active – heat sink system	12.5 °C	-	18.67%
15	Elminshawy et al. [94]	Experimental investigation of a novel alternative cooling system.	Active – Earth-to-air heat exchanger (EAHE) for pre-precooled ambient air flow.	-	18.90%	-
16	Masoud Rahimi et al. [95]	Examining how coolant flow pattern affects a PV cell's cooling by contrastingtwo different microchannel designs.	Active – Water as working fluid in single-header and multi-header microchannel.	-	-	28%
17	Abdüssamed Kabakus et al. [96]	Analysis of electrospray cooling for PV panels.	Active – Electrospray cooling with water as the coolant fluid.	32.2 °C	-	56.6%.

18	Hassan Raad et al. [97]	Theoretical evaluation of benefits of various watercooling methods in terms of energy, money, and the environment.	Active – Jet water impingement cooling (JWPV) and evaporative cooling (EPV).	-	-	1354.10R ~kWh
19	Mays N. Shaeli et al. [98]	Jet cooling's experimental impact on solar cells with PCM and varying diameters.	Active –Jet cooling with two jet diameters (5 and 8 mm) and PCM.	-	9.4	-

4.3 Hybrid cooling techniques

Combining passive and active cooling methods in photovoltaic (PV) systems is a powerful way to manage heat effectively, which extends the life and energy conversion efficiency of the PV module. Temperature control and power output have been significantly improved by hybrid systems, especially those based on phase change materials (PCMs) combined with active modes like thermoelectric cooling (TEC). When compared to traditional PV systems, a hybrid PV/PCM/TEC system reduced peak temperatures by 9.28 °C and increased electrical output by 9.69% [99]. Additionally, study showed that SCA-optimized active water-cooling systems with proportional-integral-derivative (PID) controllers also demonstrated superior thermal performance, with considerable water savings, a 34.5% decrease in average PV temperature, and a 9.46% increase in power generation [100]. Table (3) provides a quick overview of different hybrid cooling methods. Real-time thermal optimization as a function of changing environmental circumstances is made possible by the complementary functioning of active and passive cooling, which also minimizes energy consumption during cooling operations and maximizes system efficiency overall. By reducing heat stress and degradation, complementary technique optimizes PV performance and module life [101]. In order to prepare the way for the mass-level deployment of renewable energy technologies, intensive research efforts are focused on developing innovative active cooling technologies, enhanced thermal stability, and cost-effective PCM-based systems [102].A hybrid system enables an adaptive cooling mechanism in which passive solutions are sufficient for lower thermal loading regimes and active components dominate at high solar irradiation levels to maintain effective heat dissipation. By keeping the PV panels consistently within their ideal operating temperature range, the heat treatment lowers running costs and improves the sustainability of solar power systems as a whole.

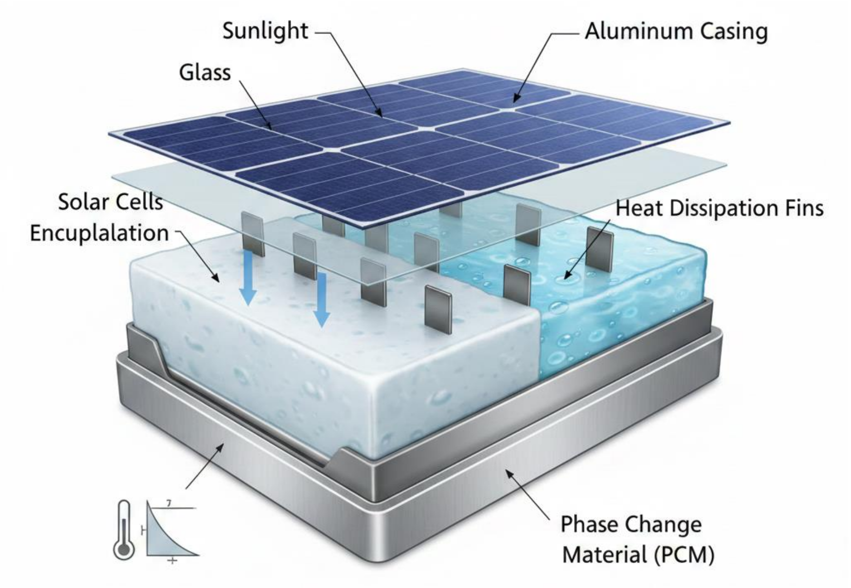

Fig. 11. Schematic of a Photovoltaic Panel with PCM-Based Hybrid Passive Cooling System [103].

Table 3. An overview of studies on Hybrid cooling methods.

No.	Author	Study	Technique	Temp. Drop	increase Efficiency %	increase Power
1	Mustafa K. Ahmed et al.[104]	Experimental- PV/T panel	Hybrid – water + air	2 ^{o}C	-	3–4 W/hr
2	Mustafa K. Ahmed et al.[105]	Experimental- PCM + Al_2O_3 integration	Hybrid – wax + microparticles	-	6	-
3	Emad Jaleel Mahdi et al.[106]	Numerical- Ground-source cooling	Hybrid – underground pipe system	28%	-	6.5%
4	Yusoff et al.[107]	Numerical- Heat sink +hydrogel + water spray	Hybrid – active + passive	-	-	30.59W
5	Eid et al.[108]	Numerical-TECs + thin water film	Hybrid – dual cooling	17.27 ^{o}C	11.23	-
6	Nese B. Ziyadanogullari , Yunus Ozdemiret al. [109]	Experimental- Nanofluid pipe cooling	Hybrid – Al_2O_3/TiO_2 nanofluid	-	8.32	-
7	Zainal Arifin et al.[110]	Experimental and Numerical- TiO_2-based nanofluid	Hybrid – PVT system	8.5 ^{o}C	2.11	-
8	Muhammad Farhan et al. [19]	Numerical- Soy wax PCM for hot climate	Hybrid – passive thermal PCM	18 ^{o}C	10.89	-
9	Daniele Colarossi and Paolo Principi [111]	Numerical- PCM + graphene + fins	Hybrid – composite cooling system	-	3	-
10	P.K. Tyagi [112]	Experimental- MWCNT + paraffin wax	Hybrid – dual cooling	-	-	13.25%

11	A.Y. Bhat and A. Qayoum [113]	Numerical- Ternary nanofluids + PCM slurry	Hybrid – fluid + geometry	-	32	-
12	A. Hamada et al. [114]	Experimental-PCM + water-based PVT	Hybrid – dual active/passive	-	74.1 / 34.6	-
13	A.M. Bassam et al. [115]	Experimental- SiC nanofluid + micro-fin tube	Hybrid – nano-PCM + nanofluid	-	9.6	-
14	A. Kouravand et al. [116]	Experimental- CPV-T + nanofluid + finned PCM	Hybrid – CPV hybrid system	26.6 °C	-	17.02 %
15	Ismail Al-Masalha et al. [117]	Outdoor evaluation under hot climate	Hybrid: water spray + air	24 °C	-	13%
16	Ayesha Khan et al. [118]	Long-term PV/PCM/TEC experiments	Hybrid: PCM + TEC (with free convection)	9.28 °C	-	9.69%
17	Mohamed B. Ben Hamida et al. [119]	CFD of parallel-flow PV/T	Hybrid: air + water (dual mode)	5.35 °C	-	13.33
18	Mohamed A. Alnakeeb et al. [120]	2-D simulation of PVT-PCM (ANSYS Fluent)	Hybrid: water cooling + PCM (half-elliptic tube)	-	66.28	-
19	Amin Shahsavar et al. [121]	Lab study: cooling PCM by cold-water mist	Hybrid: PCM + ultrasonic cold-water mist	27.3 °C	-	47.22%
20	Ashraf K. Maryood et al. [122]	experiment -back-side fins	Hybrid: back-side fins + surface water flow	22–18–15.6–18.5 °C	11.5 to ~12.3–13.3–12.0	-
21	Engin Şimşek et al. [123]	Parametric model vs water-only	Hybrid: water channel + bottom PCM layer	-	1.6–3.8	1.4–7 kW
22	Dhafer M. Hachim et al. [124]	Experimental and numerical (modules: PV, PV-TEG, PV-TEG-HS)	Hybrid: TEG + heat sink	32%	-	-

Table 4. provides a quick comparison of solar panel cooling techniques, highlighting the advantages and disadvantages of each approach. The findings show that active techniques produce faster cooling rates and performance stability at the expense of higher energy consumption and higher costs, whereas passive techniques are easy to integrate and have low energy consumption, but are less effective in hostile environments. Climate, resource availability, and economic viability all play a role in choosing the best method.

Table 4. Advantages and Disadvantages of Different Photovoltaic Panel Cooling methods and techniques.

Cooling methods			Advantages	Disadvantages	Efficiency	Cost
Phase Change Materials (PCM)			• Passive thermal storage accumulates heat through phase change to reduce panel temperature rise. • Smooths temperature fluctuations and stabilizes panel temperature over extended periods. • Simply integrated in back layers or panel structure with little mechanical complexity. • Comparatively uncomplicated system that has no moving parts. • Environmentally friendly cooling; reduces overall system energy consumption.	• Inherently limited thermal storage capacity relative to active systems; requires proper integration design. • Efficiency is reduced above PCM melting point; degradation after multiple thermal cycles. • Heat distribution problems in PCM; requires thermal conductivity promoters for better performance. • Chances of leakage or degradation of PCM properties with time, especially after repeated cycles. • Material selection must consider chemical safety and long-term stability.	10.89%	Moderate capital cost.
Fluid cooling	Nanofluids		• Tremendous increase in thermal conductivity of refrigeration fluids, enhancing heat dissipation. • Enhanced cooling performance with little system size increase. • Electric and thermal properties adjustable based on concentration and nanoparticle type. • Applicable in active cooling systems, lowering overall energy use. • Improves thermal system stability and reduces hotspots.	• Costlier to produce than conventional fluids. • nanoparticle stability and sedimentation over time. • Greater fluid viscosity can negatively affect pump and fluid flow performance. • Possible health and environmental impacts induced by nanoparticles. • Needs careful consideration of chemical compatibility with cooling system materials.	22.81%	High initial investment for nanomaterials.
	Water	Spraying water	• Active and efficient cooling by evaporating water quickly, reducing panel temperature. • Easy-to-use and straightforward approach that can be used on a large scale. • Dust and dirt settling on the surface of panels is reduced, enhancing performance. • Comparatively low running cost when compared to other mechanical cooling techniques. • Panel efficiency greatly increased in hot and arid regions.	• It requires a lot of water, which can be unsustainable in water-scarce areas. • Needs a water distribution system with high efficiency and accurate control of sprayed amounts. • Deposition or corrosion on the surface of panels possible from exposure to water. • Effectiveness of cooling is relative to ambient temperature and relative humidity. • Hard to apply in windy conditions where water spray gets dispersed.	7-9.2 %	Moderate operational cost
		Immersion water	• Very effective cooling through submerging panels in water with very high heat transfer possible.	• Requires special equipment to provide electrical insulation and prevent direct contact with electric components.	20%	Moderate infrastucture cost

			• Panel temperature reduced significantly and efficiency increased. • Can be combined with closed-loop cooling systems for conserving water. • Minimizes dust and dirt accumulation on the panel surfaces. • Improves stability of panel operation under extreme environmental conditions.	• Added weight and size can affect structural design of the system. • Large water consumption if efficient recirculation systems are not used. • Corrosion and rust hazards due to permanent exposure to water. • More complicated maintenance and cleaning compared to other cooling types.		
	Air	Natural air	• system with no moving parts that is easy to install and requires little upkeep. • It uses ambient airflow to naturally lower the temperature of solar panels. • It is a passive cooling method that requires no additional energy. • indirectly increases the longevity and efficiency of the panel. • Low upkeep and inexpensive.	• little effect on lowering the temperature when exposed to intense sun radiation. • To encourage airflow around the panels, engineering design may be necessary. • Cooling effectiveness is influenced by wind direction and speed. • Limited cooling impact, particularly when humidity and temperature are high. • Ineffective in enclosed spaces or poorly ventilated metropolitan environments.	5-10%	Very low cost.
		Ducted air cooling	• Can be designed according to site conditions and size of the panels. • It can be combined with other cooling techniques like forced or natural air cooling. • A more uniform decrease in panel temperature and an increase in overall system efficiency. • Increases cooling efficiency by improving the direction and dispersion of airflow over panel surfaces. • Concentrates cooled airflow and minimizes losses from air dispersion.	• Additional electrical energy usage when combined with forced air fans. • The installation of ducts requires more room, which may limit their use in some applications. • Careful design is necessary to prevent pressure losses and guarantee uniform air distribution. • Higher installation and maintenance costs, as well as a more sophisticated system. • Reduced efficiency due to obstructed ducts or insufficient airflow	11-18%	Moderate cost.
		Forced air	• Adaptable designs appropriate for a range of sizes and applications. • Enhances panel efficiency significantly, particularly in hot weather. • It can be combined with intelligent control systems to improve energy efficiency and performance. • By forcing air over panel surfaces, active and efficient cooling is achieved. • Optimizing cooling performance is possible with an adjustable airflow rate.	• Increased system complexity and the need for regular fan maintenance. • higher installation and operating expenses in comparison to passive cooling. • higher noise levels produced by fan operation. • and higher electrical power consumption for fan operation	8.2%	Low capital cost

Radiative cooling	• Passive cooling without additional energy consumption; no moving parts or pumps; silent and eco-friendly. • Can lower panel temperature below ambient, especially at night. • Compatible with selective coatings that enhance radiative emission and reduce solar absorption. • Simple installation and low maintenance due to lack of moving parts. • Zero greenhouse gas emissions; improves PV efficiency and performance.	• Reduced effectiveness under cloudy or high humidity conditions; limited daytime cooling under direct solar radiation. • Dependent on clear sky and weather conditions; limited cooling of the rear surface. • Challenges in developing durable, high-emissivity materials compatible with PV panels. • Limited commercial deployment; insufficient long-term reliability data. • Geographic and seasonal impact on effectiveness; difficulty in dynamic temperature control.	5%	High initial cost for specialized coatings.
Heat sink	• improves heat transfer from the solar panels to the surrounding environment, lowering cell temperature • Available in various designs suitable for different operating conditions (air-cooled, water-cooled, metallic, etc.) • Can be manufactured from high thermal conductivity materials such as aluminum and copper • Supports both active and passive cooling techniques • Improves solar panel efficiency and extends system operational lifespan.	• Increased weight and size may affect the structural design of the solar panel • Requires periodic maintenance, especially for water-cooled systems to prevent corrosion and clogging • May increase the overall system cost • Heat sink performance is influenced by ambient wind speed and temperature • Improper heat sink design can lead to poor thermal performance and uneven heat distribution	18.67%	Low to maderate cost.
Heat pipe	• Highly effective at rapidly and efficiently transferring heat from the heat source to the cooling area. • Simple and durable design with no moving parts, which reduces maintenance requirements. • Readily integrated with passive and active cooling systems. • Low mass compared to traditional cooling systems with the same performance. • Can operate in various orientations and conditions.	• Relatively high initial manufacturing cost compared to traditional cooling methods. • Performance can be degraded by air gaps or improper installation reducing efficiency. • Efficiency dependent on working fluid properties and wick material characteristics. • Risk of leakage of working fluid in the pipes after a while. • System design requires precision to ensure effective thermal conduction and avoid hot spots.	15%	High manufacturing cost.
Reflective coatings	• Reduces solar radiation absorption by reflecting the majority of incident sunlight, lowering panel surface temperature. • Passive solution with no energy consumption or moving parts.	• Efficacy depends on coating durability and resistance to environmental degradation (UV, dust, moisture). • Potential reduction in electrical output if reflectance also reduces	3%	Very low cost.

	• Simple to apply to various panel surfaces and materials. • Raises overall PV efficiency by reducing thermal losses. • Typically low-cost and straightforward to produce and apply.	useful light absorption by PV cells. • Requires occasional maintenance or recoating to provide reflectivity over time. • Low cooling capacity in comparison to active cooling methods. • Able to alter optical characteristics and appearance of panels, influencing acceptance and integration.		
Thermoelectric cooling	• Management of precise temperature by electrical current; weather-independent; quick response. • Able to actively lower cell temperature, improving efficiency and reliability. • Modular and scalable; potential integration with PV/T systems to tap heat. • Solid-state operation with no moving parts; very low maintenance. • Potential to increase the overall efficiency of the PV system; no direct emissions.	• Increased electricity consumption can reduce the net energy gain. • Low efficiency of conventional TEC materials; requires efficient hot-side heat removal. • Performance depends on thermal contact resistance and mechanical integration complexity. • Performance degradation with time due to material aging and environmental exposure. • High upfront cost, heavier weight, and dependence on rare materials; complexity in best control.	9.5%	High cost

5. Future directions and mitigation techniques

5.1 Emerging materials

The photovoltaic cooling technology also continues at a pace of rapid high-speed development driven by discovery and application of high-performance materials whose thermal and optical behaviors are optimized [120]. Of these, nanostructured PCMs, graphene composites, and photonic metamaterials are among the most popular. They all contribute to increased heat storage density, thermal conductivity, and infrared emissivity, hence increasing radiative cooling efficiency [121]. For instance, graphene nanoparticle or multi-walled carbon nanotube (MWCNT) hybrid phase change materials possess improved thermal response and temperature regulation compared to common materials such as paraffin or hydrated salts [125]. Furthermore, photonic films with high mid-infrared emissivity and visible light transparency allow for passive cooling below the ambient temperature even under direct sunlight illumination [126]. In the case of photovoltaic cooling systems, the qualities of recyclable biomaterials are also determined by attaining high-performance and environmentally friendly characteristics [127]. With the addition of new materials that have shown good results in improving thermal conductivity, such as graphene-reinforced composites and carbon nanotubes, this diversity of properties can achieve the best thermal performance of cooling systems in reality [128]. Furthermore, even in hot climates, the combination of photonic metamaterials and high-emissivity dielectric films maximizes passive radiative cooling, lowering operating temperatures in photovoltaic panels while also promoting environmental sustainability through the use of recyclable, bio-based materials [129].

5.2 Advanced computational models

Computational modeling is used as the main method to lower the cost of designing and integrating PV cooling systems at the sacrifice of experimentation and innovation pace [119]. High-fidelity simulation of heat and fluid coupling across several cooling systems is possible through the use of computational fluid dynamics (CFD), finite element analysis (FEA), and machine learning-based optimization techniques [130]. To find geometries that maximize electric and heat transfer efficiency, for example, parametric optimization of the heat sink geometry, air flow characteristics, and PCM position can be simulated [131]. Additionally, AI-based control systems provide intelligent thermal management and energy conservation by dynamically altering cooling processes in real-time based on ambient circumstances [132]. Real-time sensor feedback is used to teach these systems. In addition to being able to monitor the system in real time, digital twins are crucial because they can track long-term performance and predictive maintenance by offering a leading predicted path [133].

5.3 Improving system efficiency

Since solar systems are not just used for cooling, their efficiency is crucial. There are numerous ways to improve system efficiency, including spectrum filtering, MPPT optimization, and anti-reflective coatings, even though heat control is crucial [134]. High-efficiency combination systems that integrate cooling with solar thermal energy harvesting (PV thermal systems) can be used to increase system efficiency and overall energy [122]. Waste heat can be dispersed by these combination systems and recovered as thermal energy that can be utilized in various places [135]. Heat burden is lessened via intelligent tilting and shade mechanisms. Lastly, the system's total energy efficiency is enhanced via energy recovery through cooling subsystems. This guarantees that the system will run continuously [136].

5.4 Addressing integration challenges

The integration of cooling systems is one of the primary obstacles to the widespread use of integrated solar infrastructure. A number of contributing elements, including structural stresses, the need for weather insulation, and electrical connections, must be taken into account while installing PV systems [137]. Additionally, space constraints and aesthetics restrict the installation of external cooling equipment in rooftop and building-integrated photovoltaic (BIPV) systems [138]. Such problems would be addressed by plug-and-play module architectures for passive or hybrid coolants, which would make deployment simple and even scaleable. For simple integration, batteries, inverters, and monitoring systems must also be provided [139]. Simplifying installation, maintenance, and even interoperability will be greatly aided by the standardization of cooling interface protocols and thermal design principles.

5.5 Ensuring reliability and maintenance

PV cooling systems need to be extremely resilient, require little maintenance, and continue to function steadily even in the face of shifting weather patterns in order to function effectively for a very long time. Because there are no moving parts, passive systems have very high reliability; however, material deterioration, especially with regard to PCMs and reflective coatings, needs to be periodically assessed [140]. Condition-based maintenance techniques are required for active systems in order to monitor component fatigue in pumps, fans, or thermoelectric modules. Real-time performance monitoring and early system failure signaling are made possible by the use of Internet of Things (IoT)-enabled diagnostics and fault detection algorithms [141]. Manufacturers and end users can also receive performance references and maintenance plans from standardized reliability test techniques conducted in various settings (desert, humid, alpine, etc.). To further reduce lifespan costs and boost system uptime, future research must focus on dust-proof coatings, self-healing materials, and non-invasive maintenance solutions [142].

6. Conclusion

Based on the review of cooling techniques, the following conclusions are drawn:

1. **Passive Techniques:** Methods such as natural convection and Phase Change Materials (PCMs) are cost-effective and low-maintenance. They are most effective in moderate climates, capable of reducing panel temperature by 10–15°C, though their cooling capacity is limited during peak irradiance.
2. **Active Techniques:** Water-based active cooling (e.g., spraying, immersion) demonstrates superior thermal performance compared to air cooling, achieving temperature drops of up to 22°C. However, the parasitic energy consumption of pumps and fans must be carefully balanced against the efficiency gains.
3. **Hybrid Systems:** PV/T hybrid systems offer the highest overall efficiency by simultaneously generating electricity and useful thermal energy. Studies verify efficiency improvements of over 10%, making them the most promising solution for high-temperature environments.
4. **Future Outlook:** Research should focus on minimizing the cost of active systems, developing advanced PCM composites with higher thermal conductivity, and integrating intelligent control systems to optimize cooling operations dynamically.

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