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TOPICAL REVIEW

The Effects of Temperature on Photovoltaic and Different Mitigation Techniques: A Review

ZUHAIR MUHAMMED ALAAS, (Member, IEEE)
Electrical and Electronics Department, Engineering and Computer Science College, Jazan University, Jazan 82817, Saudi Arabia
e-mail: zalaas@jazanu.edu.sa

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ABSTRACT This paper provides invaluable insights for enhancing the performance of small-scale home photovoltaic systems. The efficiency boost of the PV panel depends on several factors, such as cooling methods, module type and size, geographic location, and time of year. Maintaining consistent and low cell temperatures is one of the most critical factors that can dramatically impact the electrical power production of PV modules. When the temperature of photovoltaic modules (PVM) increases during operation, it leads to a decline in the output, a significant concern for engineers and users. The paper comprehensively reviews the latest developments in PV panel temperature management and cooling methods, offering an in-depth discussion of alternative PV panel cooling methods, including active and passive techniques. It covers numerous strategies and provides a comprehensive understanding of the field, ensuring no aspect is overlooked in optimizing home photovoltaic systems.

INDEX TERMS Photovoltaic temperature, active cooling techniques, passive cooling techniques.

I. INTRODUCTION

As traditional energy sources continue to deplete and the consumption of conventional energy sources accelerates, the world faces a critical global warming situation. The urgency for alternative energy solutions has never been more pressing. Solar energy, in particular, is a growing field and a beacon of hope in our pursuit of sustainable energy. The progress of societies and economies has always relied on energy availability [1]. However, with the escalating consumption of conventional energy sources, greenhouse gas emissions have also surged, exacerbating the critical global warming situation. In this context, transitioning to more efficient energy conversion and modifying the energy distribution network is not just important. It is a matter of survival [2], [3]. Renewable energy (RE) is an immediate and unavoidable necessity to identify alternative energy sources and mitigate the environmental impact of fossil fuels [4].

PV cells are one such renewable energy source (RES) that is readily available [5]. However, the low conversion rate of commercial PV modules (PVM), approximately 18%, is a significant drawback [6]. On average, only 4% to 17% of the incoming solar radiation is converted into power by PVM. The type of solar cells used and the operating environment influence conversion efficiency. Consequently, heat is generated from more than the incident sun energy; thus, the PVM will experience undesired short- and long-term losses. Typical short-term losses include rising module temperature, decreasing electrical yield, and reduced module efficiency. However, a long-term loss is defined as permanent structural damage to the module caused by a continued heat stress period [7]. The operating temperature is one of the essential elements that can impact the PV panels' efficiency. Temperature can affect the voltage and current of solar panels and ultimately impact photovoltaic efficiency, which can be observed on the panels' I-V curve. As the temperature rises, the efficiency of electricity generation decreases linearly [8], [9]. The conversion efficiency of crystalline silicon solar cells decreases by 0.4-0.5% with each degree of temperature increase [10]. Thus, it's critical to lower the working temperature of PV cells to maximize panel efficiency and prevent permanent cell damage [11].

In an attempt to reduce the temperature of PVM, numerous researchers have worked to develop efficient active and

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passive cooling methods. Pumps and fans are mechanical components that demand additional electrical energy when using active approaches [12], [13]. Conversely, passive methods use heat sinks and natural convective heat transfer to cool PV systems. The heat exchangers attached to the rear of the modules that keep the PVM at a steady temperature are called heat sinks [14]. Heat sinks offer significant promise as a cooling component in photovoltaic systems because they don't require electricity [15], [16]. Another passive cooling system uses air heat sinks to lower the PVM's back surface temperature. It comprises modules with and without heat sinks and modules with heat sinks arranged as thick, rectangular fins and fins with holes. The investigation found that the module with fins on the back had a 50% drop in temperature [17]. The roughness of the absorber plate and wall of the channel was artificially increased to enhance heat transfer from the PVM, thereby effectively reducing the operating temperature and improving efficiency. However, increased roughness of the wall and absorber incurred a pressure drop penalty and required higher pumping power [18]. According to [19] and [20], Various rib configurations in the air channel can improve heat extraction efficiency, but doing so raises friction losses noticeably. According to [21], several doable changes are needed to enhance heat flow in the air conduit. This review's main goal is to investigate how uniformly lowering solar cell temperature can improve the performance of small-scale home photovoltaic systems.

The main goal of this review is to comprehensively analyze the effects of temperature on the performance and efficiency of photovoltaic (PV) systems, highlighting how increased temperatures can lead to significant decreases in energy output. By evaluating various mitigation techniques—such as advanced cooling systems, materials innovation, and optimal installation practices—this review aims to identify effective strategies for enhancing PV efficiency and longevity in high-temperature environments. Ultimately, the goal is to provide insights that can inform better design and deployment practices in solar energy systems, promoting their reliability and sustainability in the face of rising global temperatures.

II. PROBLEM STATEMENT

The performance of photovoltaic (PV) systems is significantly influenced by temperature, which can lead to reduced efficiency and energy output in varying climatic conditions [22]. This review aims to systematically analyze the effects of temperature on PV technology, exploring how elevated temperatures can negatively impact electrical performance and lifespan [23], [24]. Additionally, it will evaluate various mitigation techniques, such as cooling systems, material innovations, and design modifications, to enhance the operational efficiency of PV systems under high-temperature conditions [25], [26]. By synthesizing current research, this study seeks to provide insights into practical strategies for optimizing PV performance and ensuring sustainable energy production in a warming world [27].

III. TEMPERATURE EFFECTS ON PV EFFICIENCY AND POWER GENERATION

A. TEMPERATURE IMPACT ON PV EFFICIENCY

The most important feature of a PV panel is its capacity to convert solar radiation into electrical power with minimal energy loss. Scientists and engineers have put much effort into improving the efficiency of photovoltaic (PV) panels. Some methods they have tried are minimizing interband absorption, reducing irradiance losses through light trapping, and reducing resistive losses in series and shunt resistors [28], [29], [30]. Researchers must focus on this crucial area of study because it depends on both the operating temperature of PV cells and the efficiency of solar energy to electricity conversion. Numerous literature reviews highlight how the operating temperature affects the maximum power produced essentially linearly [31]. Most solar energy that strikes a PV panel is represented as thermal energy. Because of the high temperature, this heat energy causes the panel's output power to deteriorate [32], [33]. The total generation of the PVM is lowered due to the PV cell's rising temperature, which also causes a significant drop in voltage and a slight increase in current [34]. Power and efficiency are closely related to the different types of PV cell technology. For every degree Celsius temperature rises in a polycrystalline PVM, the efficiency drops from 0.35 to 0.8 percent [35]. On the other hand, when the temperature increases by 1oC, silicon crystalline PV cells' efficiency decreases by 0.5% [36], [37]. It has been observed that the efficiency of solar modules is directly related to the intensity of solar radiation. However, it is inversely proportional to the temperature increase from standard conditions [38].

Therefore, overheating brought on by excessive solar radiation and high ambient temperatures is the greatest challenge to the operation of PV panels. The solar cell's electrical power output is related to its output voltage, known as the PV characteristic while keeping the module temperature and sun irradiance constant. As the temperature of the solar cells rises, the maximum power output of the cells drops, as illustrated

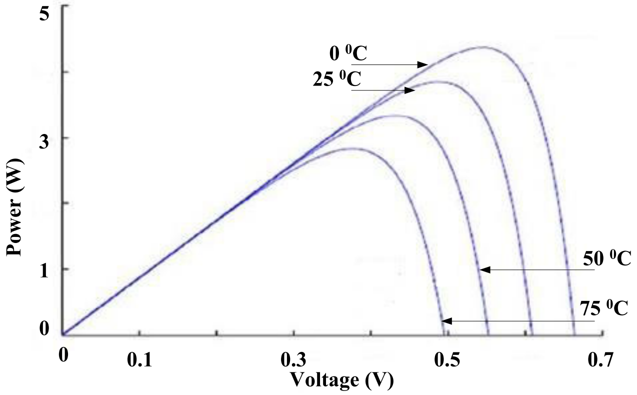

FIGURE 1. **P-V Properties of module temperature [39].**

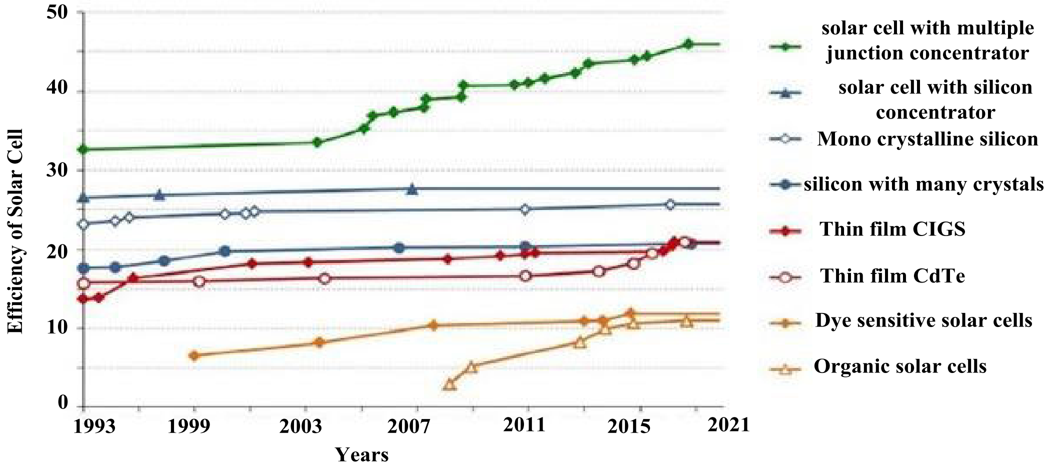

FIGURE 2. Laboratories-based PV technologies various efficiency [40].

in Figure 1. This suggests that the PV panels' production may be considerably impacted by warmth [39].

The primary problems with the relatively new PV technologies are their high overall cost or their applicability (limited) to particular uses. The most efficient photovoltaic (PV) technology currently available is HIT PV panels, which boast a record energy conversion efficiency of approximately 25.6%. Notably, this percentage excludes concentrator photovoltaic (CPV) systems, which achieve even higher efficiency levels of over 40%, as shown in Figure 2.

Conversely, conventional energy conversion efficiency, the most common among Si-based photovoltaic technologies, typically varies from roughly 10-15% in real terms, depending on the area [40].

B. TEMPERATURE EFFECTS ON POWER GENERATION

This coefficient, for a PVM, indicates how much the temperature of the PV cell impacts the module's power generation. This temperature coefficient has a negative value because the PV cell's power output decreases as its temperature rises. In [41]The 250W PVM model's temperature coefficient is $-0.44\%/1\ ^{o}$C. This means the module's maximum power decreases by -0.44% for each degree when the temperature rises above 25^{o}C. On the other hand, an increase in power output beyond the module-rated value is anticipated when the module surface temperature falls below 25^{o}C. Figure 3 illustrates how the surface temperature of solar panels affects their power output [42]. In [43], The study evaluated the cell efficiency of three types of PV cells: mono-crystalline, polycrystalline, and thin films. The researchers used the exact mounting structure dimensions, azimuth angle, tilt angle, and inverter size to record their findings over a year. Thin films exhibited less temperature dependency than mono-crystalline and polycrystalline materials, with a temperature coefficient of -0.0984%, while mono-crystalline and polycrystalline materials had coefficients of 0.109% and 0.124%, respectively. In a study [44], researchers used statistical decomposition techniques to examine the performance of several types of PV cells in Singapore throughout the year. They found that the CdTe, micro-morph Si, and amorphous Si cells experienced degradation at a rate of 2%. In contrast, mono-crystalline Si cells degraded less than or equal to 0.8%, and multi-crystalline Si cells experienced slightly higher degradation at 1%. The CIGS cells, on the other hand, exhibited an extremely high rate of deterioration at 6%. Furthermore, the study observed that all thin-film cells experienced a decrease in the filling factor and open-circuit voltage, but this was not observed in crystalline cells.

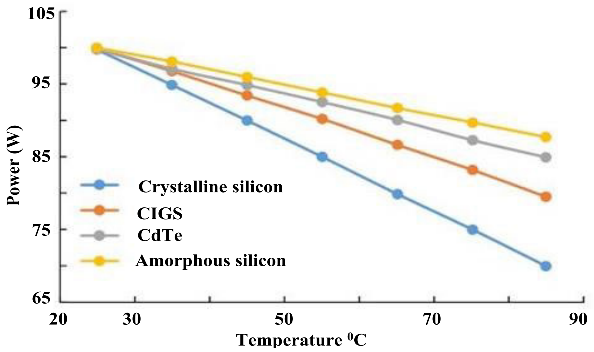

FIGURE 3. Power-temperature curve for various solar panels [42].

IV. PV PANEL COOLING TECHNIQUES

External climate variables such as sunlight, wind speed, moisture, air temperature, and concentrated dust can affect changes in surface temperature. Since changing other parameters can be challenging, it is better to lower the operating temperature to increase efficiency. For example, designing PV panels on vertical and non-directional surfaces like building facades can be challenging due to unpredictable solar radiation. Several cooling methods have been tested and

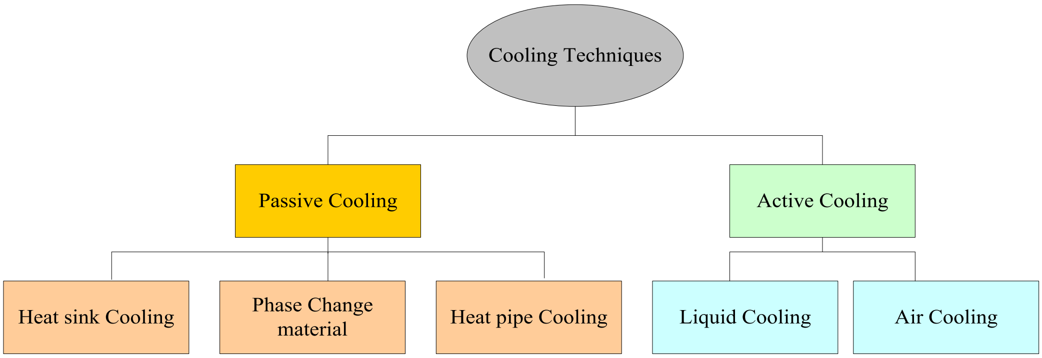

FIGURE 4. Flowchart of different cooling techniques [51].

documented in various literature to mitigate the problem of rising temperatures and increase the efficiency of PV [45]. In [46], novel cooling techniques were introduced to address the issue of heat during PV usage. The cooling process has a significant advantage as it boosts the electrical output. However, cooling requires a different heat removal method [47]. The development and upkeep of the system can be costly, and these expenses will likely balance out the advantages of the increased electrical supply. Thus, in most research, the overall electrical gain can be analyzed. There are two types of cooling: passive cooling, which uses natural convection to permit heat extraction, and active cooling, which uses energy [48], [49], [50].

Active cooling systems use water, air, and nano-fluids, which require fans or pumps. In passive cooling (which doesn't require an external power source), cooling materials, including paraffin wax, eutectics, organic materials, and cotton wick, are utilized. Conversely, cutting-edge technologies encompass Peltier-based thermo-electric cooling, phase-change materials cooling, colorless and transparent silicon shielding, microporous evaporation foils, and liquid immersion cooling [15], [42]. To achieve the desired efficiency of the solar cells, cooling must occur in a cycle with the heating process. The high thermal conductivity of active cooling fluids, including nano-fluids, has demonstrated their prospective application [52]. When base fluids like water, ethylene, etc. are combined with nano-particles of various sizes, including carbides, metals, semi-conductors, and single and multi-walled nano-tubes of 1–100 nm in size, the result is a nano-fluid [53]. A flow chart illustrating various PV system cooling methods is presented in Figure 4.

A. ACTIVE COOLING TECHNIQUE

To achieve the optimal electrical performance of PVM, [54] they investigated the experimental operating temperature variation for PVM with and without an active cooling system. Active cooling of photovoltaic (PV) cells requires a coolant like water or air, which usually needs a fan or pump. On the other hand, passive cooling does not need any additional energy to cool PV cells. Studies have used liquid coolant, air, and other liquids like water or glycols to regulate and maintain the operating temperature. An important economic factor is whether the power consumption will be offset by higher power production through active cooling [8], [18]. In one study [55], a pipe was placed on the module intended to operate as a spiral exchanger for active cooling. This method showed a 13% increase in module efficiency. In another study [56], water spraying was used to cool PVM, and the researchers attempted to determine how long it would take for the module to drop to 35°C. The outcome showed that the module produced the most energy when cooling started at 45°C. Table 1 summarizes the performance characteristics and other significant parameters based on evaluating and analyzing active cooling techniques for the acquired PV systems. The table presents the values as a range of values, an average value, or a single number [57].

1) LIQUID/WATER COOLING

When the temperature of photovoltaic cells rises to high levels, air cooling may not be sufficient to maintain optimal operating temperatures, and this may lead to a decrease in conversion efficiency. To address this issue, liquid cooling provides a better option, such as using a coolant as a heat extraction medium to maintain the optimal operating temperature of the cells and increase the use of captured thermal energy [39]. There are two approaches to water cooling: front-side and back-side. In one study, a small layer of water was applied to the front side of a monocrystalline PV panel [58], resulting in a 1% increase in overall efficiency. The panel measured 0.44m^2, with a maximum water flow of about

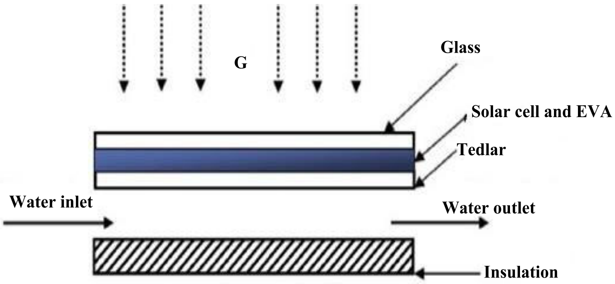

FIGURE 5. The water cooling method described in [56].

TABLE 1. Summary of relevant characteristics and general information for active cooling methods for photovoltaic.

Ref	Lowering operational temperature	Coolant	Enhanced efficiency	Increasing power output	PV Technology
[46]	5-10 ^{0}C	Air (PV/T)	4%	N/A	Si (45W)
[18]	30^{0}C		50-55.5 %	N/A	Si-poly (55W)
[60]	10-19 ^{0}C	PCM/water	1.3%	6%	Si-poly (40W)
[48]	22^{0}C	Water	14%	10.5%	Si
[56]	7.3-17 °C		15.5%	10%	Si-mono (230W)
[8]	12.5-18.5 °C		8.3% (average)	15%	Si (250W)
[61]	12.5°C		5%	N/A	Si
[62]	12- 26 °C		27.5 -36.1 %	26.1- 35.5 %	Si-mono (3.42W)
[59]	−3°C	water (CPV)	22%	16-33 %	Si-mono
[63]	15-39 °C		6-16 %	5% (average)	
[64]	N/A	water (PV/T)	2%	N/A	Si
[65]	10 °C		22.2%	25%	Si-poly (55W)
[66]	16-26 °C	Air	5–10 %	3-15 %	Si-poly (5W)
[13]	16 °C to 26 °C	Air	6.3%	15%	Si-poly(240–280 W)

1 liter/min and a pump with 0.25hp. The study achieved a 20°C drop in temperature. However, the quantity of heat lost by evaporation was not mentioned, which is something to consider when cooling from the front. In another study [59], a focused monocrystalline PV cell measuring 0.152 m2 was cooled from the back side using two aluminum pipes mounted on metal. The peak efficiency increased by 0.8% at 0.035 kg/s of water mass flow, and the PV temperature peaked at about 60°C. In a third study [56]Using a closed case that created a water flow, a 1.24 m^2 monocrystalline PV module was cooled from the back side. The study achieved an increase in efficiency, as shown in Figure 5.

A water pump with a power of 0.5hp moves a mass flow of 0.06kg/s at maximum capacity. By cooling the module, a maximum efficiency gain of 2.8% can be achieved at the cost of a 10°C drop in temperature. Although the efficiency gains are remarkable, the cooling process is complex and requires constant water flow. In one experiment, a PV cell with an area of 0.56m2 was washed with 0.03kg/s of water, which resulted in a drop in temperature of 12.5°C on the rear and 8°C on the front [67]. This resulted in an up to 4W increase in power yield; however, the efficiency gains were not measured. The pumping energy required for the water circulation system must be considered when using this cooling method. Active cooling technology can run water circulation through solar-powered D.C. pumps, making the process more efficient. Many water-active cooling technologies have been studied, and Table 2 lists some of the most successful ones [45].

TABLE 2. Active water cooling systems: Advantages and disadvantages [45].

Drob in temperature	Disadvantages	Advantages	Method
40 ^{0}C	Performance decreases on overcast days, and ionized water seems to impact performance.	Highly effective and environmentally friendly	Fluid submersion
Max 20 ^{0}C	Part of the cooling water is being wasted	Efficient, straightforward procedure	Spraying water
20-30 ^{0}C	Equipment Deterioration Causing Increased Expenses	Highly efficient water reuse	Water circulation that is driven by external forces

a: CASE STUDY 1

A study was conducted to develop a water circulation system to cool the rear surface of a solar panel actively. They tested the system in a hot climate in Dhahran, Saudi Arabia. The system consisted of a PV/T panel, a water reservoir, and a water circulation system, as shown in Figure 6. The surrounding air temperature was approximately 21°C, and the wind speed was 1.5 m/s. The researchers recorded a maximum solar irradiance of 979 W/m^2 and an average of 710 W/m^2. To optimize the output from the PV panel, the researchers also installed an MPP tracking system [56]. The research found that the maximum water flow rate was 3.6 liters per minute, with an average range of 0.91 to 2.52 liters per minute. The average working temperature of cooled PV panels was 30.5°C, whereas the average temperature of non-cooled PV panels was 37.8°C, according to the derived numerical analysis. The maximum operating temperature reduction at the PV panel's backside surface was around 17°C. PV panels' electrical efficiency reached a high of 15.8% to 18.0% in

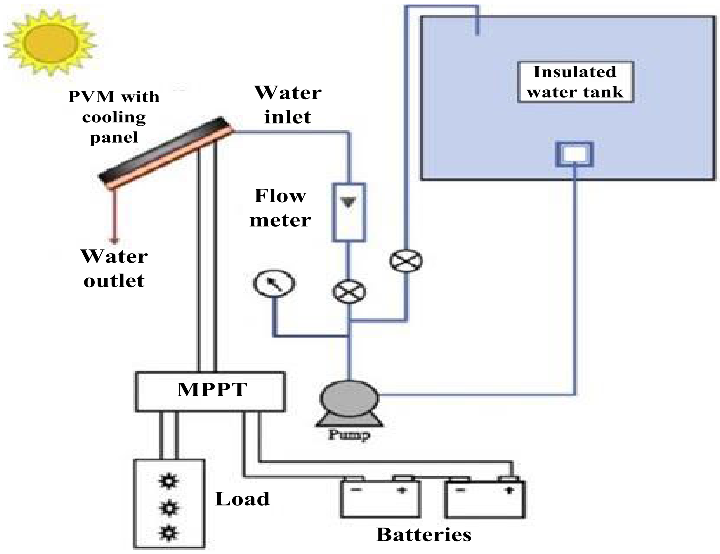

FIGURE 6. Experimental schematic design [56].

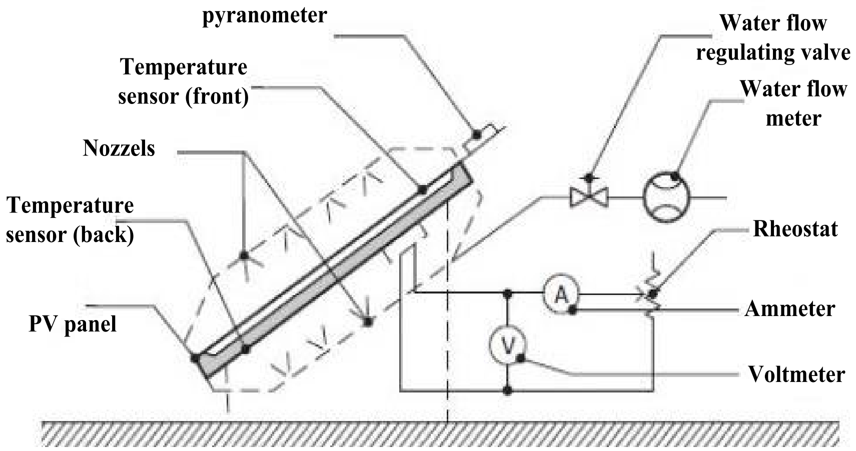

FIGURE 7. Diagram illustrating the particular experimental setup [18].

terms of performance. PV panels that were not refrigerated had an efficiency range of 15.2% to 15.7%, but those that were cooled had an efficiency range of 16.2% to 18.4%. PV power production increased by 10% on average, reaching a maximum of 185 W for non-cooled panels and 211 W for cooled ones [55].

b: CASE STUDY 2

Twenty nozzles were utilized to cool the photovoltaic (PV) panel from both sides simultaneously, with ten nozzles installed on each side, as illustrated in Figure 7. Cooling scenarios were tested individually for the front, rear, and sides of the panel, and these were then compared to a scenario without cooling. Water spray cooling positively impacts PV panel performance when both surfaces are cooled simultaneously [18].

The study conducted in [68] investigated the impact of water spray cooling on the efficiency of solar water pumping. Two configurations were used in the experiment: case A, which had two modules and a water spray of 25 liters per hour per module, and cases B1 and B2, which had three modules with water sprays of 5 liters/hour per module and 25 liters/hour per module, respectively [69]. As shown in Figure 8, the module temperature decreased in cases A and B1, with case A experiencing a more significant reduction than case B1. Based on the experimental findings, spraying water on the PVM significantly improved the system's performance [70]. In a study conducted in [71], the performance of PV panels was tested experimentally using the water cooling method. The solar simulator used for the indoor test consisted of twenty 500 W halogen bulbs. Two 50W mono-crystalline PV panel units were used for the test, with one panel used as the base panel and the

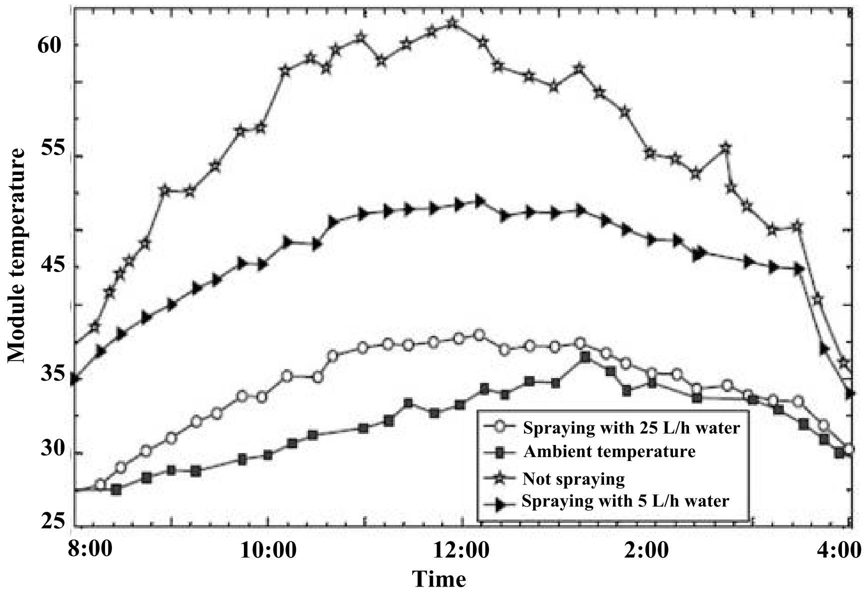

FIGURE 8. Impact of water spray on the temperature of the module [70].

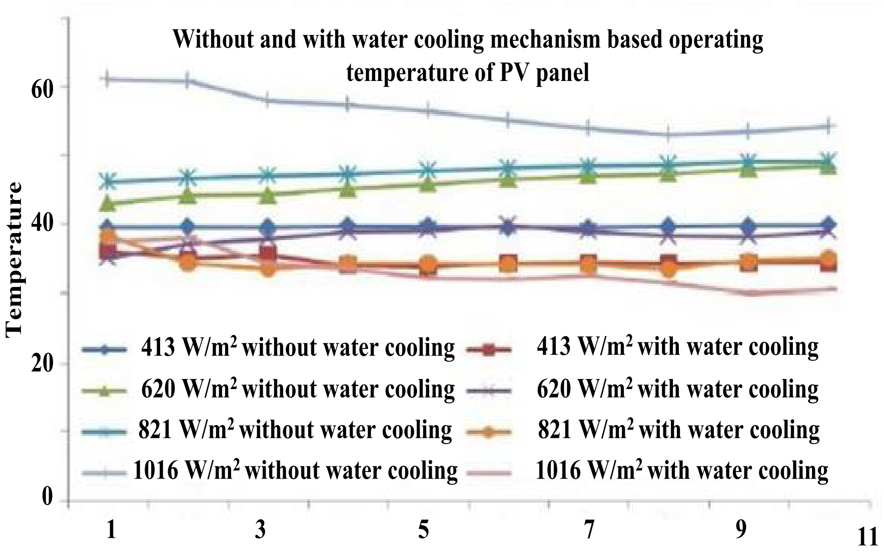

FIGURE 9. PV panel operating temperature without and with water cooling system [74].

other used to spray water using a DC water pump attached to its front surface [72]. The experimental results showed that the power output of the PV panel with a water cooling system improved by 9-22 %, while 5-23 °C lowered the operating temperature [41]. As a result, Figures 9 and 10 indicate that water cooling enhances the PV panel's electrical efficiency [73], [74].

c: CASE STUDY 3

As part of the experimental setup, water nozzles were installed on the front and rear surfaces of the PV panels and connected to the water distribution system. This setup is shown in Figure 11 and Figure 10. The system was tested in a typical Mediterranean climate with maximum solar radiation ranging from 810-850 W/m^2 and ambient air temperatures between 27^{0}C and 30^{0}C. Additionally, the air velocity was less than 1 m/s [75].

Several cooling methods were tested on photovoltaic panels using a water spray approach. The cooling techniques included front-only, back-only, and simultaneous backside and front cooling. The simultaneous cooling method showed the best results with a maximum temperature drop of 30°C [76]. This cooling method resulted in a net increase in PV panel electrical efficiency of 5.9%, despite the total progress of 14.3% [77]. The operating temperatures for the PV panels were reduced by 23 to 32 degrees Celsius, resulting

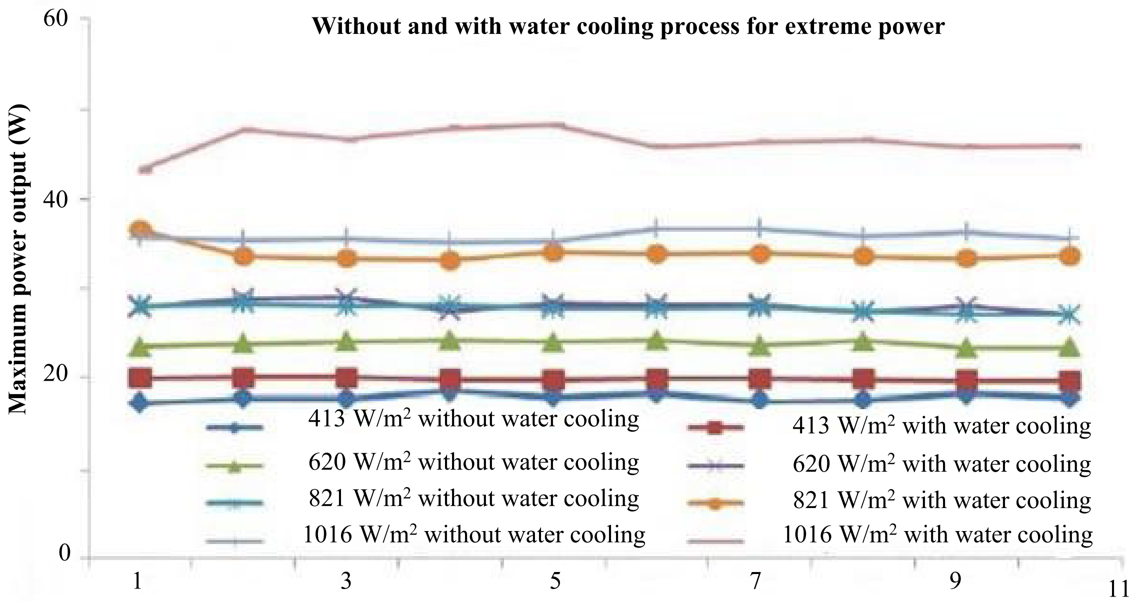

FIGURE 10. Peak power generations of PV panels with and without water cooling systems [73].

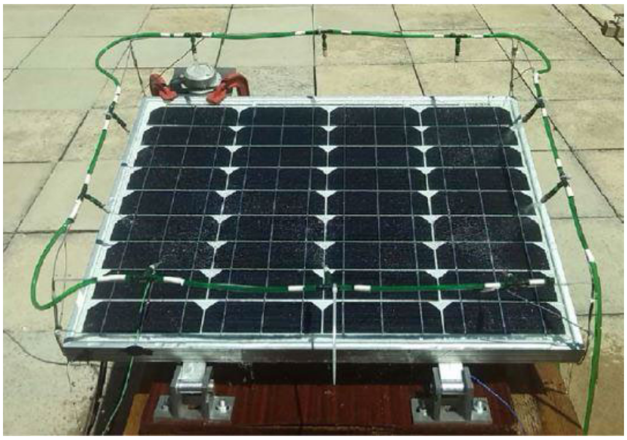

FIGURE 11. Method of cooling with water spray [75].

in efficiency gains of 12% to 14.3% (net improvement of 3.6% to 5.9%) [78]. The increase in PV panel power production ranged from 14.0% to 16.0%, with a net improvement of 5.4% to 7.7% [79]. An economic evaluation of the suggested water spray technique showed it was feasible, as more electricity was generated than needed for the circulation system's labor. However, the evaporation effect as a water spray cooling technique and its overall impact on the economic side was not investigated. Furthermore, the effect of a changing water spray temperature was not examined, which would have helped assess the performance response in terms of economic viability [80].

2) AIR COOLING

Active air-cooling systems utilize fans or other methods to generate airflows. These systems can effectively use waste heat produced by solar panels. As a result, mounting fin-equipped metallic materials on the rear surface of a solar panel to increase air circulation can significantly enhance its cooling [81].

In [13], the authors experimented with PV panels using forced and natural air as the working fluid on a building's rooftop. The research concluded that the panel between the air gap and the roof needed to be high enough to allow air to flow in for adequate cooling and higher efficiency to lower the solar cell temperature successfully. The high temperature on the steel rooftop significantly impacted the peak power of the natural convection model, which was approximately 7.5%. In contrast, the forced convection model demonstrated twice as much electrical output at a surface temperature drop of roughly 15 degrees Celsius. The forced and natural convection model for a PVT system is displayed in Figure 12. In [82], the authors used a monocrystalline PV panel to investigate a photovoltaic thermal air-based collector. An air-based thermal collector is necessary to extract heat from the PV panel and utilize it to heat buildings because combining the thermal collector and PV panel results in a surface temperature jump. The study found that the electrical and thermal efficiency of the system was 15% and 22%, respectively. To maintain the temperature of the photovoltaic system below 40°C, it is recommended to establish an air gap between the walls and the system. Forced airflow solutions include ducting beneath solar panels, metal frames, fins, and open-air channels.

The array ducts can significantly reduce the temperature of solar panels and increase their efficiency by 12% to 14% [13]. Active air cooling systems are preferred due to lower startup and operating costs than other options [83]. Though air-based technology is less effective due to the low density and heat capacity of air, it is still helpful in hot, rural climates with limited water resources. An experimental study on an

(a) Natural convection

(b) Forced convection

FIGURE 12. PVT air system [13].

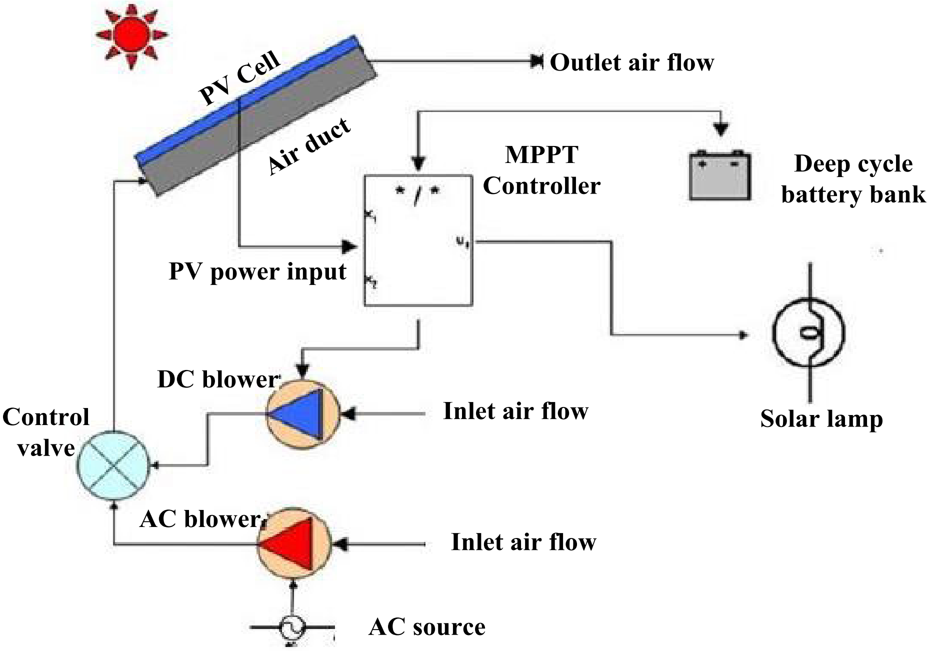

FIGURE 13. An outline of the experimental configuration [18].

active air cooling system with an open single channel and a heat removal fan showed that it could provide air mass flow rates between 0.02 and 0.08 kg/s/m^2 [84].

a: CASE STUDY 1

A test arrangement was established to evaluate the electrical and thermal efficiency of the PV/T air system. The EA building of the National University of Singapore has this technology mounted on its roof. The complete experimental setup is illustrated in Figure 13, which shows a schematic diagram [18]. This experimental setup aimed to look at how temperature impacts the power output and efficiency of photovoltaic panels when they are in use. Four 55 W polycrystalline PVMs were employed for the experiment to produce power [68]. Four deep-cycle gel batteries were used to store the electricity produced by the solar modules. Underneath the PV modules was an arrangement of air ducts that allowed air to flow through [18].

Fins were installed in the duct to transfer heat from the PV panel to the moving fluid. To guarantee equal airflow distribution, the inlet/outlet manifold was meticulously developed [85]. Air was drawn from the surroundings by a direct current blower that was battery-powered and used

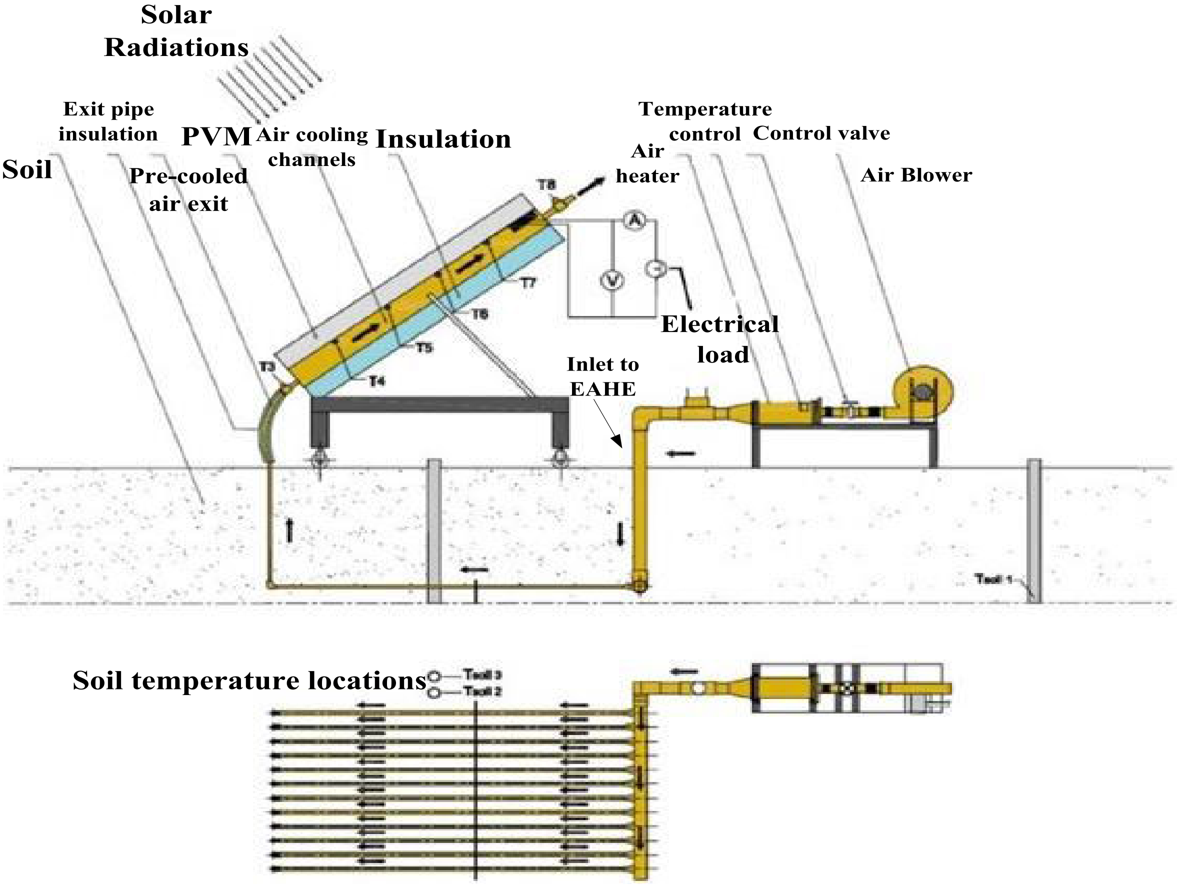

FIGURE 14. Schematic diagram of the experimental test rig [91].

FIGURE 15. An image of the experimental configuration [91].

to cool the modules. To guarantee that the most electrical power is collected during operation, an MPPT was utilized to control the power output from the solar panel [86]. This experiment also used an additional alternating current (AC) blower, which served as a variable speed blower to regulate the flow rate via the duct [87]. The time frame for the experiments was 9:30 am to 5:00 pm. A pyranometer was employed to measure the daily worldwide sun irradiation. Calibrated T-type thermocouples were used because temperature readings are crucial to this experiment [88]. The current and voltage of PV, panel temperature, air temperature at the intake and outlet manifolds, wind speed, and solar irradiation were all measured during the experiment [62].

b: CASE STUDY 2

The experimental rig configuration is located in Port-Said, Egypt, at a latitude of (310 16’ N 320 18’ E). It’s installed on a transportable support structure and tested outdoors on a college campus. To make the most of the location’s north hemisphere position, both PV modules were installed with a 300-tilt inclination towards the south [89]. The location’s latitude is close to the ideal tilt angles for south-facing photovoltaic systems to achieve the maximum annual solar radiation [90].

The PV cooling system was created by connecting the buried earth air heat exchanger (EAHE) to a flat PVM with an active area of 1.65m^2. The experimental test rig’s schematic diagram and picture are in Figures 14 and 15 [91]. Air heaters, which are electric heating chambers equipped with regulated temperature and centrifugal air blowers, were utilized in an ambient air simulator. These air heaters were used to heat the induced ambient air temperature, simulating the actual range of ambient air temperature in arid hot climatic areas [92]. To minimize the operating temperatures of the power generating module, six 0.15m x 0.15m straight air conditioning channels were built using a 3mm thick aluminum sheet to accommodate the PV’s backside entirely [93].

An air blower initially forced the ambient air into the buried EAHE. Simultaneously, pre-cooled air was directed to the cooling channels’ lower side [94]. The cooling medium, or pre-cooled air, absorbs heat from the PVM backside and releases it through the upper side of the cooling channels. The cooling ducts were insulated at their backs using glass wool. The airflow rate through the buried EAHE can be regulated manually using flow control valves [95].

B. PASSIVE COOLING TECHNIQUE

1) HEAT SINK

It was suggested in [96] a possible cooling method for solar cells is to use a heat sink, a metal with high thermal conductivity. The study explored the numerical temperature reduction of PV panels on a clear summer day using various configurations of ribbed wall heat sink of air and passive cooling. The results showed that the maximum temperature of the panel at an angle of 45° was lower than that at an angle of 135°. When a heat sink was used, the maximum power generated by the PV panel increased by 6.97% and 7.55%, respectively, compared to the reference scenario for rib angles of 45° and 90° [97]. Heat sinks with high thermal conductivity are mounted at the back of solar panels to improve convective heat transfer from air to the panel sink [98], [99]Using heat sink plates is an affordable and easy way to cool PV panels, but not many physical experiments have been done on this approach. Figures 16 and 17 show micro-channels that are also suitable for high heat capacity transmission. Table 3 provides some examples of the work that has been done on using heat sinks to cool PV panels.

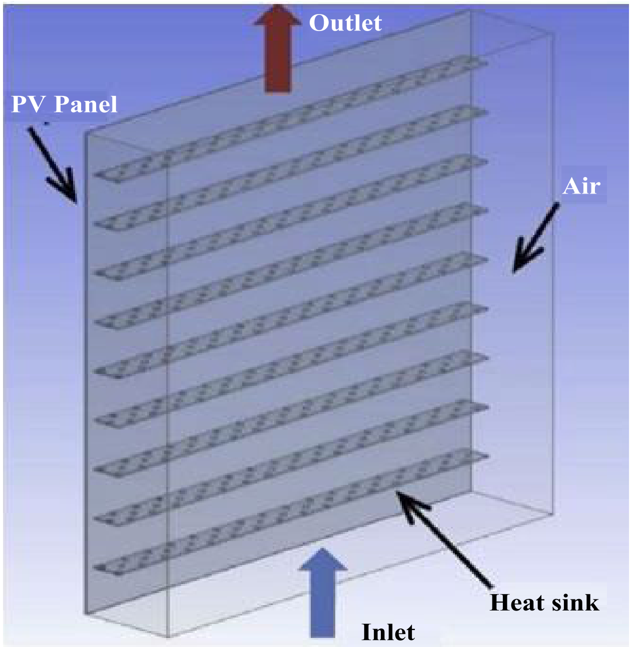

FIGURE 16. PVM with heat sink.

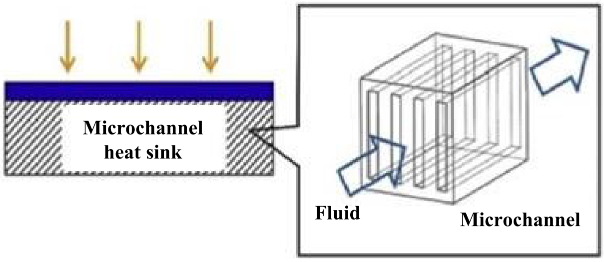

FIGURE 17. Microchannel heat sink diagram [100].

2) PHASE CHANGE MATERIAL

PCMs are compound materials that can absorb and release thermal energy, allowing for temperature control. When PCMs undergo a physical transition, such as the melting-freezing cycle, they release or absorb large amounts of heat known as “latent.”. PCMs can be made using oil, eutectics, and inorganic salt hydrates [51], [101]. In Japanese houses, a functional PCM system uses air to cool panels. The building’s ceilings and roof contain PCM, which is charged by a 4.2kW grid system, reducing the need for heating and cooling [36]. In this particular instance, a paraffin-based PCM that melts between 38 and 43 degrees Celsius was placed behind a panel, as seen in Figure 18. The use of PCM for cooling increased the power generation of the panel by 5.9% when compared to the annual electricity generated by the panel in hot temperature conditions. Additionally, cooling was reduced during extreme heat and cold periods due to partial melting and solidification [102]. A numerical study conducted in [103] found that the inclination angle and

TABLE 3. Heat sink cooling techniques.

Ref	Electrical parameters	Cooling agent	Key findings	Cell temperature	cooling system
[100]	VOC and MPP values have increased by 10% and 18.67%.	Air	A Computational Fluid Dynamics (CFD) simulation was conducted on an aluminum plate heat sink featuring perforated fins.	The temperature has decreased from 85.3°C to 72.8°C.	Heat sink
[98]	Electrical properties have increased by 6.05%.	Aluminum fins & Copper	Copper fins are more efficient and provide superior electrical performance compared to aluminum fins.	C.U. fins helped achieve a uniform temperature throughout the module, which wasn't possible with aluminum fins.	Wick structure and Heat sink
[99]	The efficiency has increased by 2.72%.	Fins	Economical and experimental studies were conducted.	The temperature is expected to drop by up to 7.4°C.	Heat sink

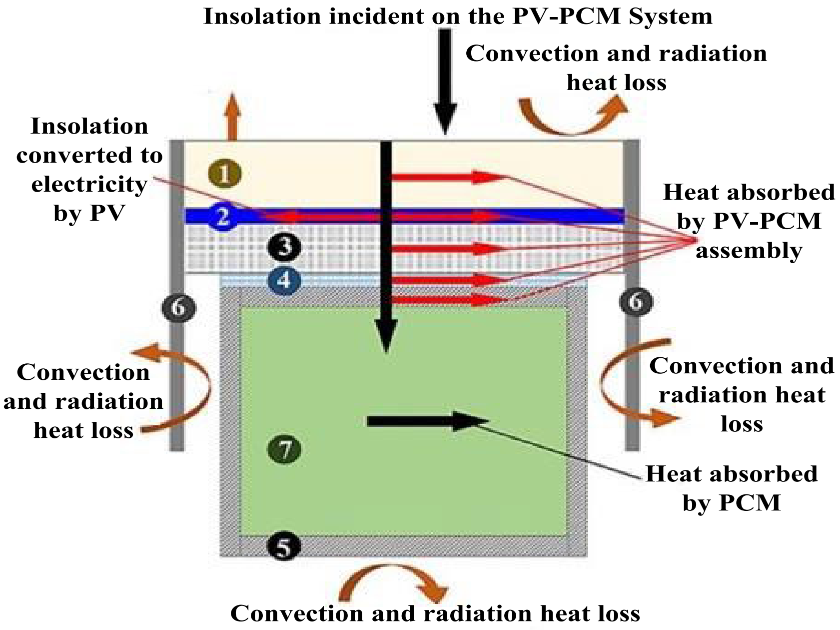

FIGURE 18. Schematic of a PV-PCM system [102].

heat transmission in PCM substantially impact the operating temperature of PV panels. In [104], an experimental investigation was carried out using the MATLAB Simulink Toolbox for the PV-PCM system. The study showed that utilizing this system improves the yearly energy efficiency of the PV panels in hot climates by 5.9%, as presented in experimental research with PCMs [105]. The PV/PCM system obtained the best results using a steel tank and 42–44 paraffin. The effects of the PCM container's operating conditions were examined in [106]. The results demonstrated that container depth and azimuth angles benefit energy storage. In [107], a study was conducted to assess the correlations between the power, temperature, and efficiency of photovoltaic panels using various cooling methods. The study found that the most significant increases in efficiency were 22% for liquids, 21.2% for PCM, and 20% for air.

3) HEAT PIPE COOLING

Heat pipe cooling (HPC) is a promising technology for cooling solar panels [16], [108]. Traditional columnar heat pipes and flat solar panels have a high thermal contact resistance, which results in inefficient heat transfer. However, as suggested by the author in [109], a new network of micro-heat pipes addresses this issue due to its flat design, which makes good contact with the solar panel.

In [110], a heat pipe was employed to cool a 1cm2 PV cell irradiated with 40W/cm^2 of waste heat, and the highest temperature of the water was 48°C. The cell's maximum temperature differential with the surrounding air was 43°C. Similarly, in [97], a 0.0625m^2 PV panel was cooled via a heat pipe, resulting in a 2.6% gain in efficiency and a 4.7°C drop in temperature at maximum light. The power yield increased by a maximum of 8.4%. Figure 19 shows the temperature differential of the cell in [111]. The size of the cell and the heat pipe are roughly the same [110]. While it is easy to apply cooling to concentrated PV cells, using this method for large-scale models is questionable [112]. One study used water to cool the HP condensing side passively, resulting in a 3% efficiency boost [113]. In another study, heat pipes were used to cool a mono-crystalline PVM with a 0.150m^2 area [114]. Water boxes were added to the condenser end of the heat pipes to improve HP cooling and act as heat storage devices [115]. In [110], a heat pipe was employed to cool a 1cm^2 PV cell irradiated with 40W/cm^2 of waste heat, and the highest temperature of the water was 48°C. As a result, the rear side temperature dropped by about 13°C during summer and spring measurements, resulting in an average gain of 1.2W and a relative increase in efficiency of about 6% [116]. It is worth noting that using heat pipes to cool PV cells this way is a practical solution [117].

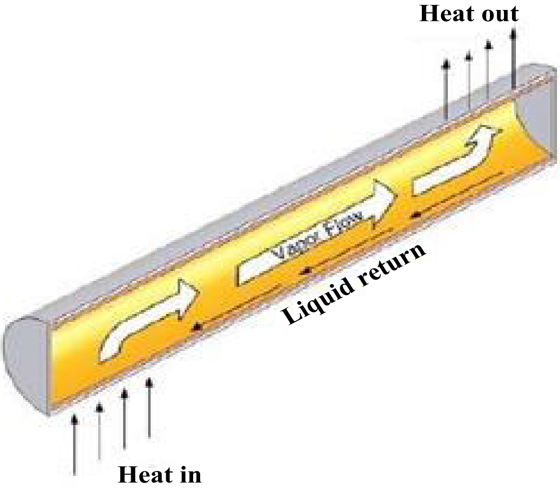

FIGURE 19. Mechanism of the heat pipe [110].

Active cooling techniques for PV panels involve mechanical systems like fans or pumps to reduce temperature, offering significant efficiency improvements, especially in high-heat conditions, but at the cost of additional energy consumption and complexity. In contrast, passive cooling relies on natural methods, such as airflow management and reflective surfaces, to dissipate heat without any energy input, making it more straightforward and cost-effective. While passive cooling is more accessible to implement and maintain, it generally achieves less dramatic temperature reductions than active methods. Ultimately, choosing these techniques depends on climate, budget, and desired efficiency outcomes.

V. COMPARATIVE ANALYSIS IN TERMS OF IMPROVEMENT IN EFFICIENCY AND COST

To conduct a comparative analysis of cooling techniques for a solar power plant, we can focus on several standard methods: passive cooling, evaporative cooling, and active cooling (e.g., water or air cooling). Each of these techniques has distinct costs and efficiency improvements.

A. PASSIVE COOLING

- **Description**: Involves designing solar panels and systems to minimize heat absorption. Techniques may include reflective coatings or optimizing tilt angles [124].
- **Cost**: Generally lower initial investment, as it often requires no additional equipment. Costs may come from design adjustments [125].
- **Efficiency Improvement**: Can improve performance by 5-10% under optimal conditions, depending on local climate [126].

B. EVAPORATIVE COOLING

- **Description**: Utilizes water to cool the air around solar panels. This method can lower the temperature of the panels, thereby increasing efficiency.
- **Cost**: Depending on the scale and technology used, initial setup costs for a medium-sized solar plant can range from $15,000 to $50,000. Operating costs include water and maintenance.
- **Efficiency Improvement**: This typically offers a 10-20% efficiency gain, especially in arid regions with high temperatures.

C. ACTIVE COOLING (WATER OR AIR COOLING)

- **Description**: Involves mechanical systems that actively cool the solar panels, usually through water or air circulation.
- **Cost**: High initial investment, potentially exceeding $100,000 for a larger plant, and significant ongoing energy and maintenance costs.
- **Efficiency Improvement**: It can enhance efficiency by 15-25%, particularly beneficial in consistently hot climates.

D. TRADE-OFFS: EFFICIENCY VS. COST

- **Initial Investment**: Passive cooling has the lowest cost but limited efficiency gains. Active cooling requires a substantial investment but offers the highest efficiency boost.
- **Operating Costs**: Evaporative cooling strikes a balance with moderate initial costs and ongoing water expenses. Active cooling may incur high energy costs for operation and maintenance.
- **Environmental Impact**: Passive techniques often have the least environmental footprint, while evaporative cooling may use significant water resources, raising sustainability concerns.
- **Location Specificity**: The effectiveness of each method can depend on the solar plant's geographic location. For instance, evaporative cooling is more effective in dry, hot climates, while passive cooling may suffice in milder areas.

VI. KEY FACTORS THAT AFFECT THE EFFICIENCY OF SMALL-SCALE HOME PHOTOVOLTAIC SYSTEMS

Several key factors influence the efficiency of small-scale home photovoltaic (PV) systems. Here are the most important ones:

- **Solar Panel Quality**: The type and quality of solar panels (monocrystalline, polycrystalline, or thin-film) significantly affect efficiency. Higher-quality panels generally convert more sunlight into electricity [127].
- **Orientation and Tilt**: The angle and direction of the solar panels impact how much sunlight they receive. Panels facing true south (in the Northern Hemisphere) at an optimal tilt angle will capture the most sunlight [128].
- **Shading**: Even partial shading from trees, buildings, or other structures can reduce a system's output. It's essential to keep panels clear of obstructions [129].
- **Temperature**: Solar panels operate less efficiently at higher temperatures. Cooler temperatures can improve performance, while excessive heat can reduce output [97].
- **Inverter Efficiency**: The inverter converts DC electricity generated by the panels into AC electricity for home use. Higher-quality inverters have better efficiency ratings [130].
- **System Size**: The size of the PV system to energy needs is crucial. An appropriately sized system can maximize efficiency and minimize wasted potential [131].
- **Maintenance**: Regular cleaning and maintenance of panels help maintain their efficiency. Dust, dirt, and debris can obstruct sunlight and reduce performance [132].
- **Local Climate**: The amount of sunlight, cloud cover, and weather patterns in the area affect energy production. Regions with more sunny days will naturally yield better performance [133].
- **Grid Connection**: Whether the system is connected to the grid (grid-tied) or is standalone (off-grid) can influence how efficiently it operates and stores energy [134].
- **Battery Storage (if applicable)**: For off-grid systems or those with battery backup, the efficiency of the batteries and their management can impact overall system efficiency [135].

Understanding and optimizing these factors can help homeowners maximize the effectiveness of their photovoltaic systems.

VII. ADVANTAGES OF ACTIVE COOLING METHODS COMPARED TO PASSIVE TECHNIQUES

Active cooling methods for PV panels offer several key advantages over passive techniques:

- **Enhanced Temperature Control**: Active cooling can achieve more significant temperature reductions, which can lead to higher efficiency and increased energy output, especially in hot climates [136].
- **Rapid Response**: Active systems can quickly adjust to changing conditions, responding to spikes in temperature or increased solar radiation, thereby maintaining optimal operating conditions for the panels [137].
- **Improved Performance Under High Load**: In scenarios where PV panels are generating maximum output, active cooling can help manage heat buildup more effectively, preventing potential overheating and efficiency losses [138].
- **Automation and Optimization**: Active cooling systems can be automated with sensors and control systems, allowing real-time monitoring and adjustments to maximize performance based on current environmental conditions.
- **Integration with Other Systems**: Active cooling can be combined with other technologies, such as thermal energy storage or building cooling systems, enhancing overall energy management and efficiency [139].

These advantages make active cooling methods particularly beneficial in environments where high temperatures significantly impact PV performance.

VIII. DISCUSSION

When comparing different cooling methods, it's essential to establish a universal cooling benchmark that considers various factors. However, this can be challenging, as it requires comprehensive data on power gain, relative and total efficiency increases, and detailed descriptions of different cooling techniques in existing literature. To obtain a more accurate comparison, it's essential to calculate the specific power gain per surface for each experiment by dividing the maximum power gain by the effective surface area of the PV cell. This level of detail is necessary for results to be considered valid and reliable. It's worth noting that this comparison method is only qualitative, as essential information must often be inferred from multiple sources. Therefore, it's crucial to carefully review and evaluate the data used in the comparison and consider potential limitations and biases in the research. By taking a thorough and detailed approach to compare different cooling methods, we can better understand the strengths and weaknesses of each approach and ultimately make more informed decisions about which methods are most suitable for specific applications. A summary of research on various cooling methods for photovoltaic systems can be found in Table 4.

Numerous studies have been conducted to determine the most effective method of cooling electronic devices. One of these studies [114] It has been shown that water cooling is more effective than forced air cooling. However, it is essential to note that water cooling efficiency can vary depending on the specific technique employed. Another study [75] discovered that a particular method [55] is only partially effective due to water evaporation occurring solely on the front of the cell. This indicates that the cooling technique must be carefully chosen depending on the cooled device.

Furthermore, a separate study [105] It was found that increasing the conductivity of the phase change material (PCM) can lead to better cooling and improved efficiency gains. Researchers have also found that the most effective

TABLE 4. An overview of the many cooling methods found in the literature.

Ref.	Electrical Performance	Finding	Cooling type	Cooling agent
[113]	The electrical efficiency increased by 4.3-8.7%.	Data was validated using TRNSYS software simulations, a temperature drop of 35 °C.	PCM	RT28HC
[104]	The electrical efficiency has improved by 5.9%.	A study was conducted with the yearly average temperature dropping to 10.5°C.		PCM-RT42
[115]	The electrical efficiency increased by 5.18%.	The system can be used for several things and can lower the temperature to 23°C.		Heat exchanger & paraffin wax
[116]	The electrical efficiency has improved by 5.39%.	The efficiency was affected by the position of the PCM, a temperature drop of 15°C.		Organic paraffin wax
[117]	The electrical efficiency range was between 12% and 12.4%.	Reducing channel depth while maintaining efficiency can achieve 15-31% thermal efficiency. Placing fins perpendicular to airflow improves performance efficiency.	Air	Air
[18]	Efficiency before cooling was 8% to 9%. After cooling, it increased between 12% and 14%.	A comparison was made between the findings of a heat transfer simulation model and experimental conclusions.	No Information	No Information
[118]	Efficiency has increased to a desirable degree.	The model underwent numerical development, resulting in removing thermal and electrical parameters.		
[119]	Lowering the cell temperature increased electrical efficiency.	The model was created by suspending a flat metal sheet in an air channel.		
[120]	Efficiency was improved by 2% by adding fins at random locations.	The system demonstrated exemplary performance in both low and high solar isolation conditions.	Heat sink	The fins have holes, and the air passes through to cool them.
[121]	"The electrical efficiency has improved by 2.72%."	Both economic and experimental analyses are provided, which show an 8.7% increase in thermal efficiency.		Air-cooled aluminum fins.
[100]	The company's V_{OC} increased by 10%, and P_{MP} increased by 18.67%.	CFD research was conducted with and without fins, resulting in a 14.65% increase in thermal efficiency with fins.		Fins have perforations, which air passes to cool them down.
[122]	38% more electricity was used efficiently	A two-phase cooling approach was proposed, leading to a 20% reduction in the cell's temperature.	Liquid	Air and water
[123]	Performance remained poor for quite some time.	The heat transfer coefficient successively increased to nearly 6000 W/m^2k.		Absorption of de-ionized water
[56]	Electricity increased by 9%.	The cell temperature decreased by 20%.		Water

cooling was observed in the study [63], which highlights the importance of considering the temperature of the cooling water. When comparing different cooling techniques, it is essential to factor in additional variables, such as fluid mass flow, as in studies [56], [61], and PCM material properties, as in the study [102]. Therefore, it is recommended to evaluate all these factors before deciding on the most effective cooling method for a specific electronic device. This will ensure that the cooling method chosen is tailored to the particular requirements of the cooled device, thus optimizing its performance and prolonging its lifespan.

IX. CONCLUSION

The impact of temperature on PV systems and the various mitigation techniques explored in this review underscore the critical importance of understanding and addressing temperature-induced performance degradation in solar energy technologies. As ambient temperatures rise, the efficiency of PV modules tends to decrease, resulting in reduced energy output and economic viability. However, innovative mitigation strategies such as passive cooling techniques, advanced materials, and intelligent system design can significantly improve PV performance under elevated temperature conditions. The research highlighted in this review demonstrates the diverse approaches available to mitigate temperature effects on PV systems, ranging from simple, low-cost solutions to more complex and sophisticated technologies. While challenges remain in implementing these techniques at scale, ongoing advancements in materials science, engineering, and system optimization offer promising avenues for enhancing the reliability and efficiency of solar energy generation. Moreover, the findings emphasize the need for continued interdisciplinary collaboration among researchers, engineers, policymakers, and industry stakeholders to accelerate the deployment of effective temperature mitigation strategies and drive the widespread adoption of solar energy worldwide. By addressing the challenges posed by temperature fluctuations, we can unlock the full potential of photovoltaic technology and accelerate the transition towards a sustainable, low-carbon energy future.

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ZUHAIR MUHAMMED ALAAS (Member, IEEE) received the B.S. degree in electrical engineering from the King Fahad University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, in 2002, the M.S. degree in electrical engineering from the University of Newcastle upon Tyne, Newcastle, U.K., in 2007, and the Ph.D. degree in electrical engineering from Wayne State University, Detroit, MI, USA, in 2017.

From September 2002 to November 2010, he was a Lecturer with the Abha College, Technical and Vocational Training Corporation. From September 2010 to June 2011, he was with Saudi Electric Company as a Power Transmission Engineer. Since June 2011, he has been an Assistant Professor and the Chairperson of the Department of Electrical Engineering, Jazan University, from 2019 to 2022. He is currently an Associate Professor with the Electrical and Electronics Department, Jazan University. His research interests include energy storage devices, power electronics, microgrids, PV systems, alternative/hybrid energy power generation systems, and motor drives. He serves as the Editor-in-Chief for *The Saudi Journal of Applied Science and Technology*.

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