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A Review On Cooling Techniques for Performance Improvement of Solar Photovoltaic Systems

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A B S T R A C T

The solar photovoltaic (PV) power generation has gained the popularity over the years with reduction in cost of manufacturing of solar cells. However, the performance of solar cells degrades with absorption of solar radiation and consequent rise in its temperature. Thus, thermal management of the PV modules that utilize some form of cooling to maintain operating temperature of cells nearer to ambient has been the object of research for some years. The cooling methods include passive cooling, active cooling and the combination of both passive and active cooling methods. This paper initially deliberates on different commercially employed solar cells and the ill-effect of increase in temperature on their performance. It is followed by the comprehensive review of literature pertaining to cooling of solar panels covering all the proposed methods to bring out state of the art in this field. The review would be useful in making the right decision while selecting the suitable method of cooling depending on local climatic conditions, economical alternatives and the resources available. It would be equally useful for the researchers working in the field to take up research on innovative, economical and sustainable cooling solutions for PV modules.

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1. Introduction

The rapid change in worldwide economic growth has rapidly increased energy consumption requirements. Fossil fuel energy has a limited stock, and its usage unfavorably disturbs the environment, contributing to the rise in greenhouse effects and increased CO_2 emissions, which have a direct impact on human life [1]. Renewable energy sources, such as wind, solar, geothermal, ocean, hydropower, and bioenergy, are alternative solutions available to tackle environmental degradation. Among these, solar energy is the most promising solution for generating electricity. Photovoltaic panels are made of silicon materials and semiconductors that convert solar power into electrical power [2]. The role, cost, and roadmap of solar energy worldwide have been reported [3]. Approximately 25% of electricity will be generated using photovoltaic panels by 2050, as stated by the International Environmental Agency [4]. Irradiation from the sun, with wavelengths between 380 and 700 nm, contributes to the generation of electricity in solar cells. Solar radiation wavelengths of 700 nm and longer do not provide sufficient energy to build electron-hole pairs [5][6]. Solar cells typically convert 5-20% of solar energy into electrical power [7][8]. With the absorption of solar irradiation and the consequent increase in the PV panel temperature, there is power loss as well as thermal degradation of the cells, thus reducing their life span [9]. Studies have shown the effect of temperature on the performance of PV panels with different materials, viz., crystalline, amorphous, and polycrystalline silicon, cadmium telluride, and copper indium diselenide [10]. A review of the advances in PV and PVT cooling technologies that employ various active and passive cooling techniques was presented, which provided insight into the improvement in the electrical and thermal efficiency of systems [11][12]. The thermal management of photovoltaic panels has been achieved by employing various cooling methods that include the transfer of heat through natural convection using extended surfaces [13][14][15]. The front surface of the PV panel, the back surface, and the combined front and back surfaces were cooled using water. Front surface cooling reduces the maximum temperature to 22-27°C apart from cleaning the surface [16][17]. The PV panel surface conditions were analyzed using evaporative cooling [18][19]. Evaporative cooling is an alternative solution for PV panel cooling, where cloth, cotton wick, wool wood, and water-soaked clay are used [20][21][22]. An experimental analysis was conducted on the PV systems with and without evaporative cooling. The cellulose pad was integrated on the back side of the PV panel and spray-cooled on the front surface. The analysis was performed for different cases, such as backside cooling, front and back side cooling, and cooling both sides using a controller. It was observed that the maximum efficiency improved by 15.8% when cooling the PV on both sides with different water flows [23]. The bottom surface of the solar photovoltaic module was equipped with an evaporative cooling pad [24]. A numerical analysis of the heat extraction from the PV panels with different coolants was also performed [25]. A numerical analysis of PV panel cooling was performed using dew-point evaporative cooling. The suggested approach was shown to sustain an efficiency of > 15% [26].

The photovoltaic panel temperature was reduced using coolants, such as nanofluids, air, and water, for industrial and domestic applications [27][28]. The other cooling methods include use of phase change materials [29]. Nanomaterials have been used in conjunction with either water or PCM to enhance the performance of PV systems [30]. The applications of PCM and ML in different fields have been reported [31][32]. Waste heat recovered from exhaust gas was stored in the PCM and utilized for different applications [33]. Radiative cooling is another method that would be quite effective in concentrated photovoltaic applications involving high-temperature and space applications [34].

The efficiency of solar photovoltaic (PV) systems is significantly affected by temperature rise, leading to reduced power output and overall system performance. Numerous cooling techniques have been explored, ranging from passive and active cooling methods to hybrid approaches for the thermal management of PV modules. However, a comprehensive and up-to-date review comparing these methods and their effectiveness, feasibility, and integration potential remains limited. A review of such methods that maintain the operating temperature of cells near ambient conditions would be helpful in choosing the best cooling strategy based on local climate conditions and available resources. Researching creative, affordable, and sustainable cooling options for PV modules would be beneficial for society.

Over the past three years, photovoltaic (PV) panel cooling research has advanced significantly, focusing on improving panel efficiency by mitigating temperature-induced performance losses.

Key developments include innovations in passive, active, and hybrid cooling methods as well as material-based solutions. Passive cooling techniques, such as phase change materials (PCM) and evaporative cooling, rely on structural and material enhancements without external energy inputs. Active cooling systems require external energy input devices, such as fans or blowers, to move air across the surface or behind the PV panels, thereby enhancing heat dissipation. Hybrid systems have also been suggested to integrate cooling with energy co-generation, such as photovoltaic-thermal (PVT) systems. Cooling techniques have been explored by researchers, ranging from passive and active cooling methods to hybrid approaches for thermal management of PV modules. However, a comprehensive and up-to-date review comparing these methods and their effectiveness, feasibility, and integration potential remains limited. Emerging materials, such as nanofluids and thermally conductive composites, have been integrated into photovoltaic (PV) systems to enhance thermal management. For instance, nanofluid-cooled systems demonstrate better heat removal owing to improved thermal conductivity compared to conventional fluids. The following subsections describe solar cell materials, the need for the thermal management of solar cells, and the categorical classification of the various cooling techniques employed for solar panels.

1.1 Classifications of solar cell materials

Solar cells convert solar energy into electrical energy. The semiconductor materials used to manufacture solar cells are categorized into the 1st, 2nd and 3rd generation on technology and materials. The classification of solar cells is shown in Figure 1 [34].

1.1.1 Polycrystalline silicon solar panel

The materials used for manufacturing polycrystalline solar cells have irregular grain boundaries and high-purity crystalline Si. The irregularity in the crystal structure creates non-homogeneity in the material. The electrical and thermal properties of polycrystalline solar cells vary with material composition. These cells are less efficient than other solar cells. The solar-cell efficiency was approximately 15–18%. The life cycle of a solar cell is over 25 years [35].

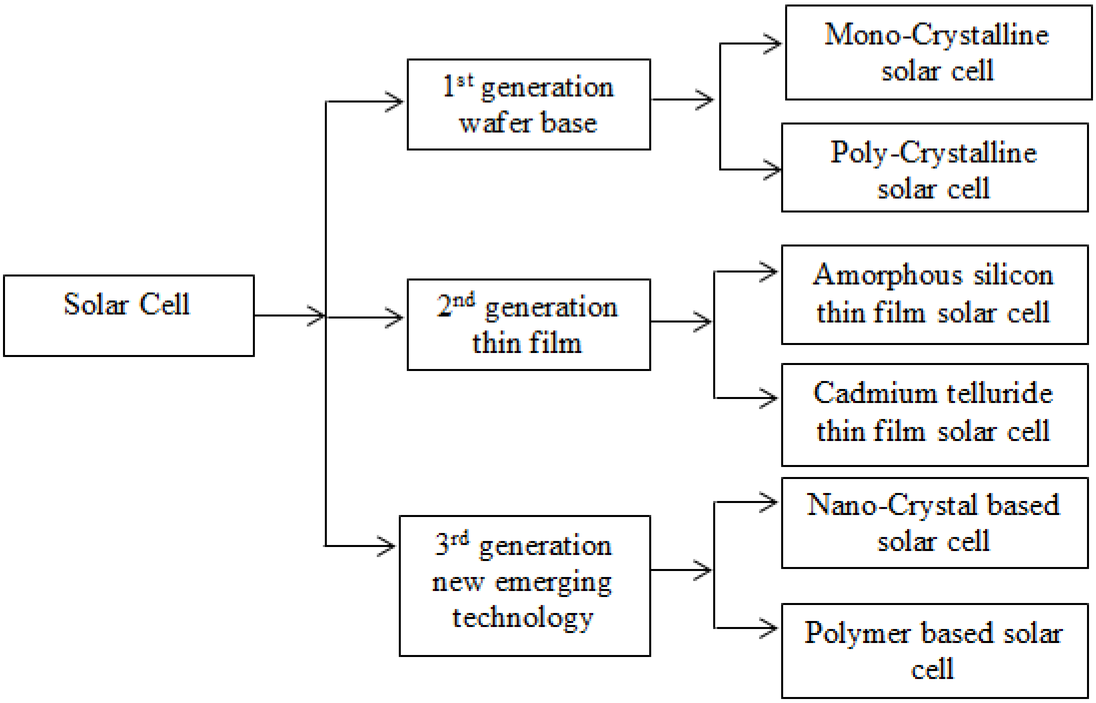


Figure 1. Classification of PV materials [34]

1.1.2 Monocrystalline silicon solar panel

Monocrystalline silicon is made from a single piece of monocrystalline material and thus has no grain boundaries. Homogeneity exists in the materials used for monocrystalline solar cells. The monocrystalline solar cell efficiency is above 20% for new panels, but decreases over time [35].

1.1.3 Thin-film solar panel

Thin-film solar cells differ from monocrystalline and polycrystalline solar cells. It is fabricated by placing a layer of PV material on a substrate. Popular variations include cadmium telluride, copper indium gallium selenide, and amorphous silicon solar cells. Cadmium telluride is a popular and commonly used drug. Thin-film solar panels are flexible and lightweight, and their maximum efficiency does not exceed 15%. [35]. Table 1 shows the classification of solar panels based on material, efficiency, and cost. New-generation solar cells include nano-crystal-based, polymer-based, dye-sensitized, and concentrated solar cells.

1.2 Need of thermal management of photovoltaic module

Out of the total solar irradiation falling on the PV panels, a maximum of approximately 20% of the energy is converted to electrical energy, whereas the remaining energy is absorbed by the panel surface, including solar cells. This absorbed heat energy is dissipated by the conductive, convective, and radiative heat transfer modes, as shown in Figure 2. It is observed that, with increase in cell temperature, the performance of solar panels decreases, which results in decrease in the conversion efficiency or electrical efficiency and degradation of the cells that reduces its life cycle [36]. Thermal management of solar modules using various cooling techniques plays an important role in maintaining a temperature close to the ambient temperature [37]. The use of cooling methods for thermal management of photovoltaic panels has been observed to increase the overall conversion efficiency and output power [38]. Figure 3 a and b shows the effect of photovoltaic panel temperature on the variations in current, voltage, and power output.

Table 1. Summary of photovoltaic modules [35]

Type of PV panels	Materials	Process of manufacturing	Appearance	Cost	Life Cycle	Efficiency η_{ref} (%)
Polycrystalline silicon solar panel	Multiple crystal of silicon	Fragments of silicon are melted together to form the wafers	Blue hue	Less expensive	25+ years	15 to 18%
Monocrystalline silicon solar panel	Single crystal of silicon	Silicon formed into bars and cut into wafers	Black hue	More expensive	25+ years	20%
Thin-film solar panel	Cadmium telluride, amorphous silicon	Putting the layers PV materials on substrate	Brown, Gray, Black	Less expensive	25+ years	15%

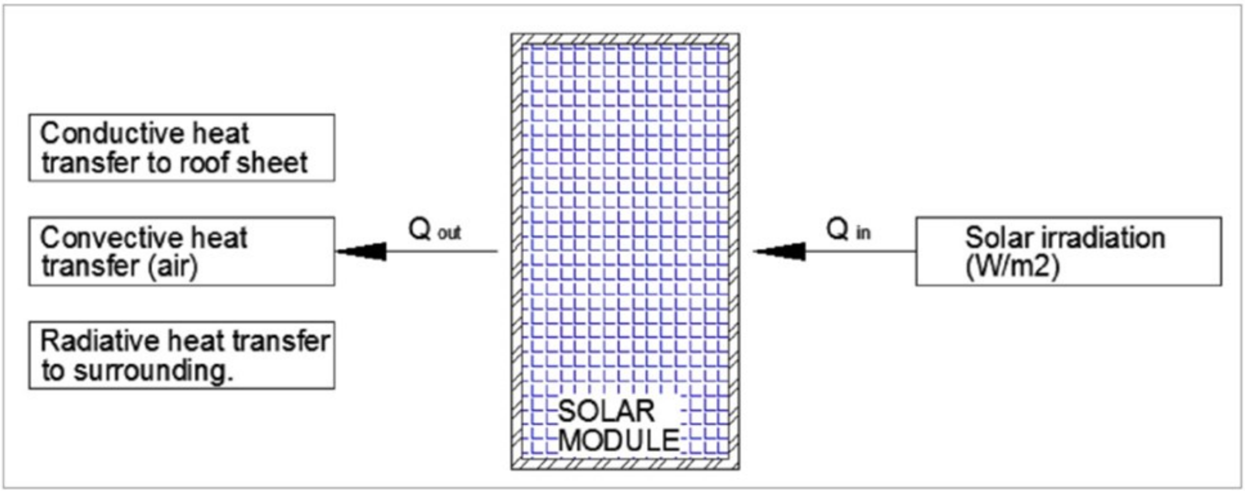


Figure 2. Heat balance of the solar module [36]

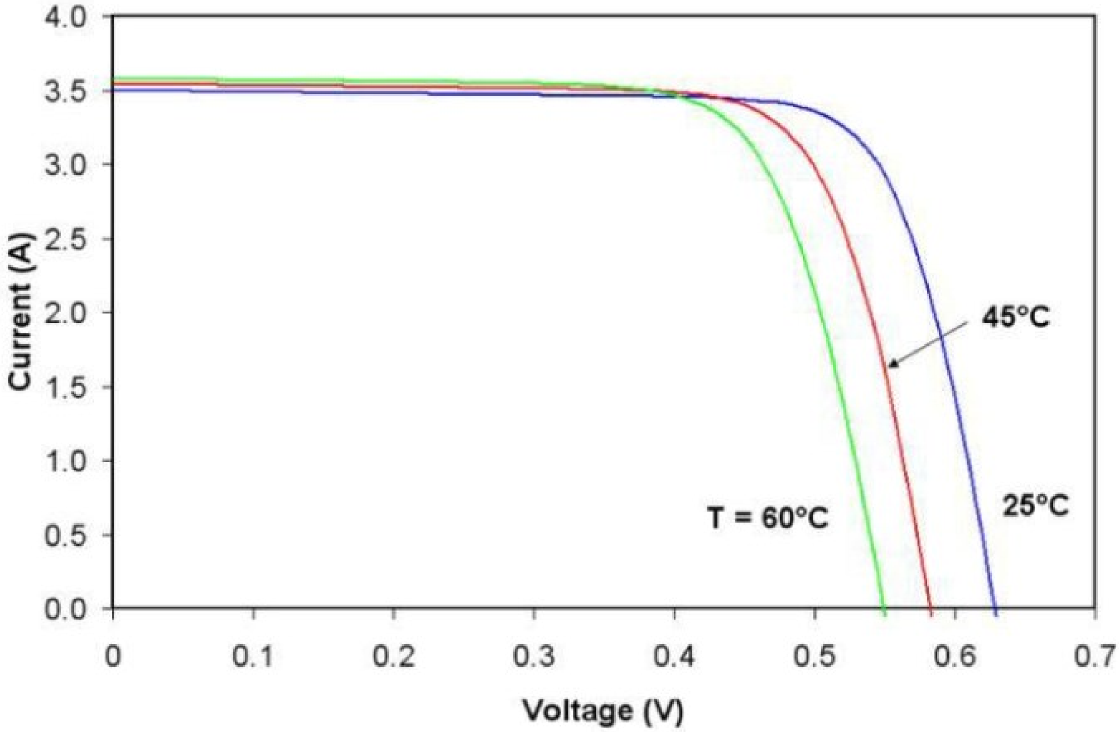


Figure 3. a) Influence of PV panel temperature on current output parameters [39]

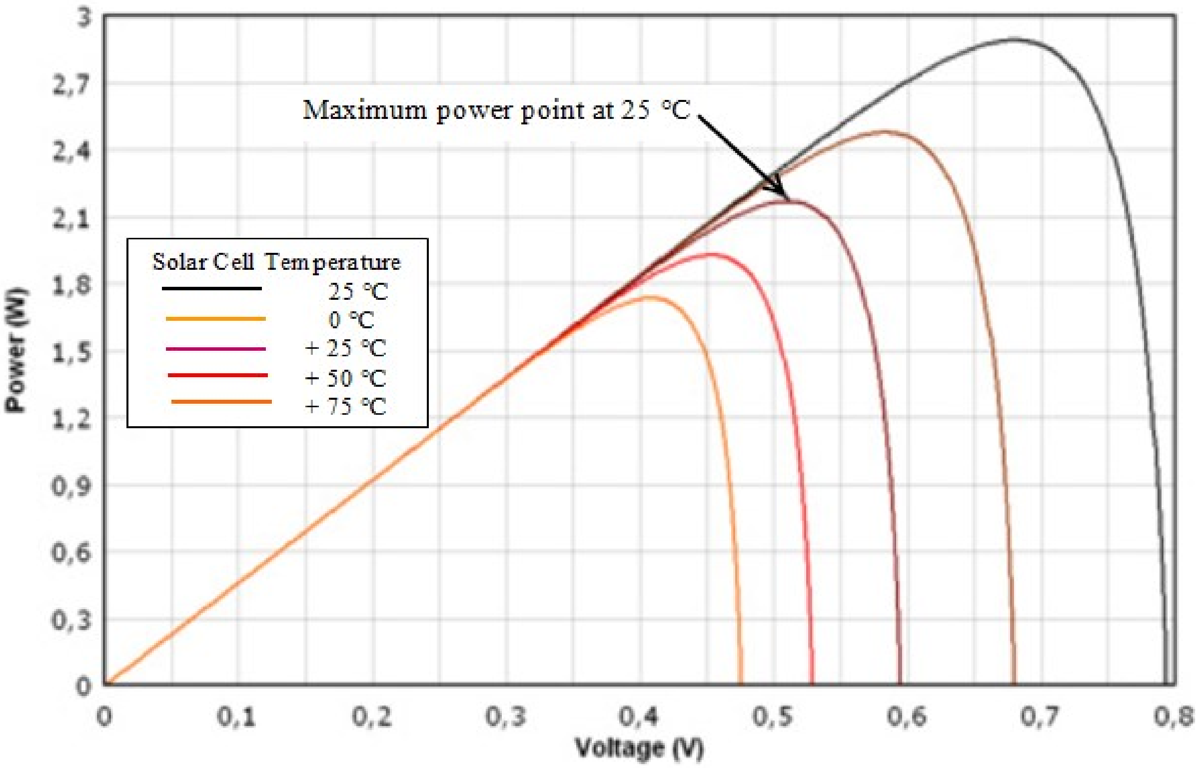


Figure 3. b) Influence of PV panel temperature on output parameters such as voltage [39].

As the temperature of the PV panel current increased slightly, the output voltage decreased [39]. The PV panel temperature increased to approximately 60–80°C, depending on the climatic conditions. It was observed that the decrease in conversion efficiency was in the range of 0.4–0.65% for every 10°C rise in the temperature of the solar panel [40].

1.3 Cooling methods

A typical classification of the cooling methods employed for solar panels is shown in Figure 4. In the active cooling method, heat is extracted from the photovoltaic panel using an external energy source of power, such as electrical energy-consuming devices. The passive cooling method extracts heat using natural convection without the help of an external energy source. Passive cooling techniques are classified into three categories: air, water, and conductive [20]. Active cooling techniques can be classified into three categories: air, water, and conductive cooling with forced air and water cooling.

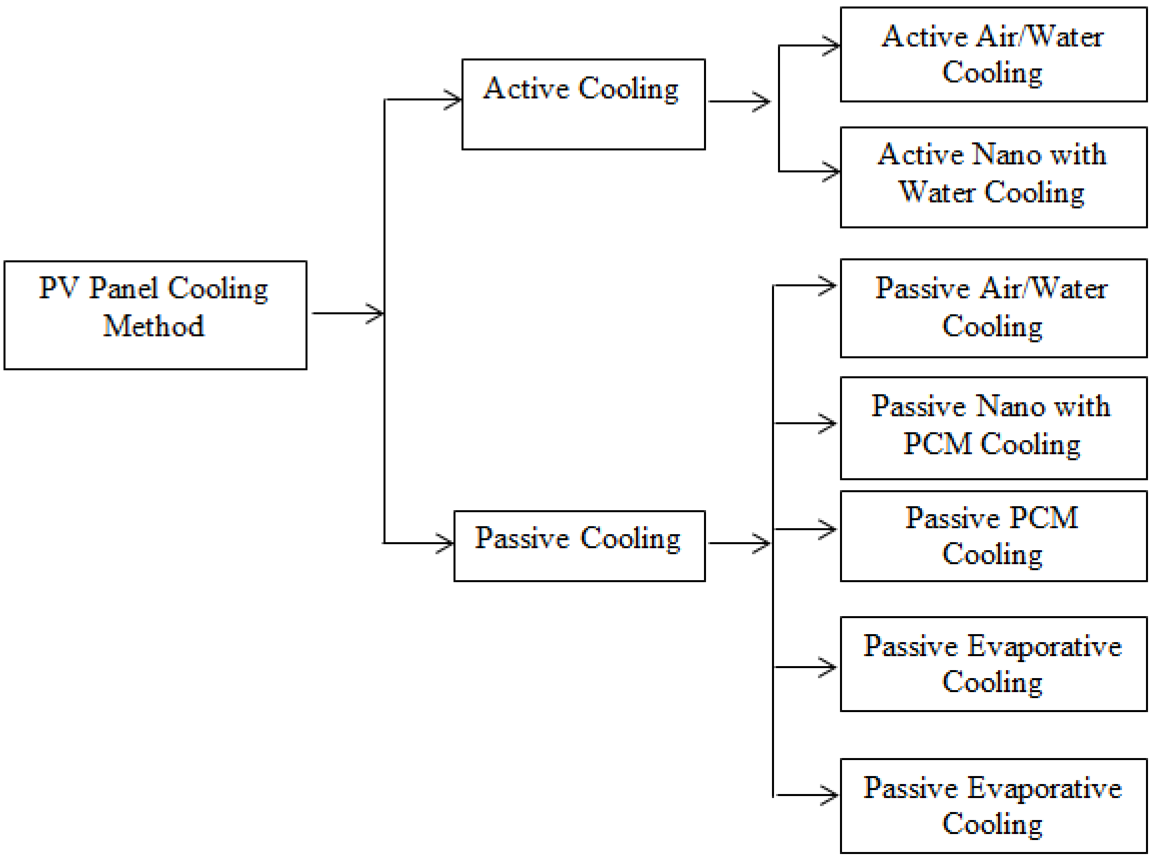


Figure 4. Classification of photovoltaic cooling techniques [1]

2. Literature Review

The literature review for the purpose of this study was carried out for various reported cooling methods. Thus, the review is divided into six subsections: (i) air cooling, (ii) water cooling, (iii) phase change materials (PCM) cooling, (iv) cooling using nanoparticles along with water and PCM, (v) evaporative cooling, and (vi) radiative cooling. The findings of this literature review are presented in the following subsections.

2.1. Air cooling

This section discusses the literature pertaining to the use of air as a cooling medium to extract heat from PV modules, lower the temperature, and improve the performance of the system.

The first study discussed the use of cold air exhausted from the heating, ventilation, and air conditioning (HVAC) system employed in a building to control the temperature of the panels. They prepared a thermal model that was validated using experimental data from literature. They observed an improvement in efficiency in the range of 11 to 18% when the lower surface of the panel was cooled with varying mass flow rates of air that depended on the cooling load of the air conditioning system, which was considered to increase from 0 (no flow) to 160 kW for a solar radiation of 500 W/m^2 [41]. The experimental setup consisted of a photovoltaic module equipped on the bottom side with a 6 mm thick sheet of phase-change material. Further, an air duct was provided on the bottom side to force the air by employing fans. The PCM melted during the day by absorbing the heat from the panel, while it dissipated the heat and solidified at night. Experiments were conducted for both free and forced air convections. It was noticed that the solar panel temperature decreased by 4.3°C in the free convection mode, while that for forced air at high, medium, and low velocities decreased by 3.4, 3.6, and 3.7 °C, respectively [42]. A wind-driven ventilator turbine was used to force free upstream air vertically upward underneath the solar panel for cooling. The wind-driven ventilator turbine was equipped with a dynamo motor for power generation. The combined power generation of the solar panel and turbine was reported to be improved by 46.57% compared to a non-cooled solar panel [43]. In buildings with photovoltaic cladded walls and roofs, the temperature of the PV panels could be reduced to 20°C when properly designed ducts were employed behind the panels that allowed buoyancy-induced flow of air. A numerical model and CFD simulations validated using measurements from the prototype were employed to predict the effect of the duct depth on the thermal and electrical performance of the system [44]. A numerical study was carried out using ANSYS-Fluent software for turbulent flow over the heat sink at the bottom of the panel. A heat sink with high thermal conductivity was used as a ribbed wall. Different configurations were selected by modifying the angle between the ribs and base plate, as shown in Figure 5. The reduction in the average temperature of the panel was found to be 41.87, 42.35, and 42.97°C, respectively, for the angles of the ribs at 45°, 90°, and 135° with base plates, while the efficiency was found to increase by 14.8, 14.7, and 14.6%, respectively [39].

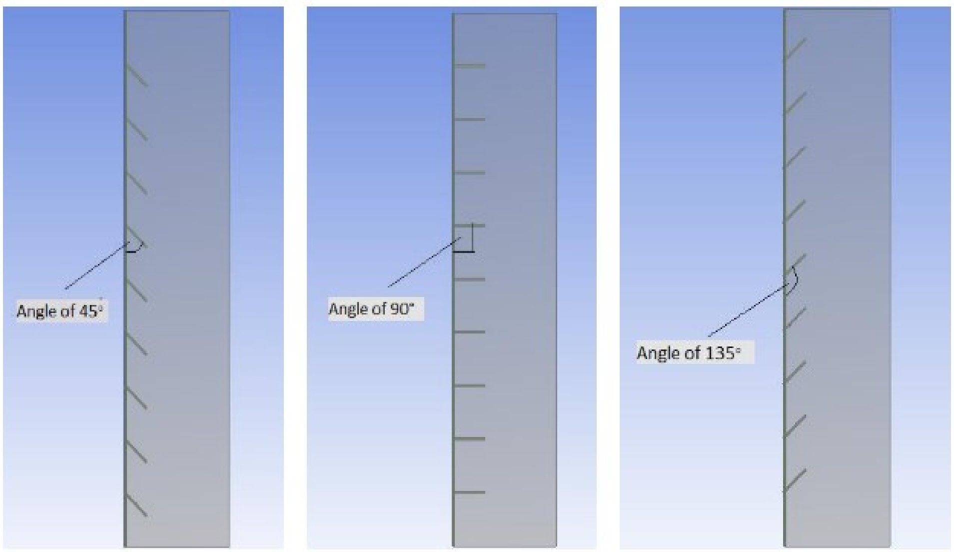


Figure 5. Inclination angles of the ribs for the studied case [39]

A CFD analysis was performed for the air-cooled heat sinks at the bottom of the solar panel. The optimized parameters like fin spacing, baseplate thickness, fin height and fin thickness were noticed to be 0.06 m, 0.0025 m, 0.12 m and 0.002 m. The average temperature drop for the optimized parameters was within the range of 25–30°C [45]. A study employing compressed air for cleaning and cooling a solar panel was reported. The increase in the output power was 30.7, 33.6, and 36.1% for air-blowing times of 10, 15, and 20 s, respectively. However, it was pointed out that the energy required to produce air flow would be higher than the energy benefit from an increased cooling duration [46]. The experiment was conducted on a bifacial photovoltaic panel by cooling the upper, lower, back and forth, and both sides using air as the coolant, as shown in Figure 6. The results showed that back-and-forth cooling gave better results in terms of thermal energy output, while the lower-side cooling method reduced the panel temperature and enhanced the electrical efficiency compared to other cooling methods [47].

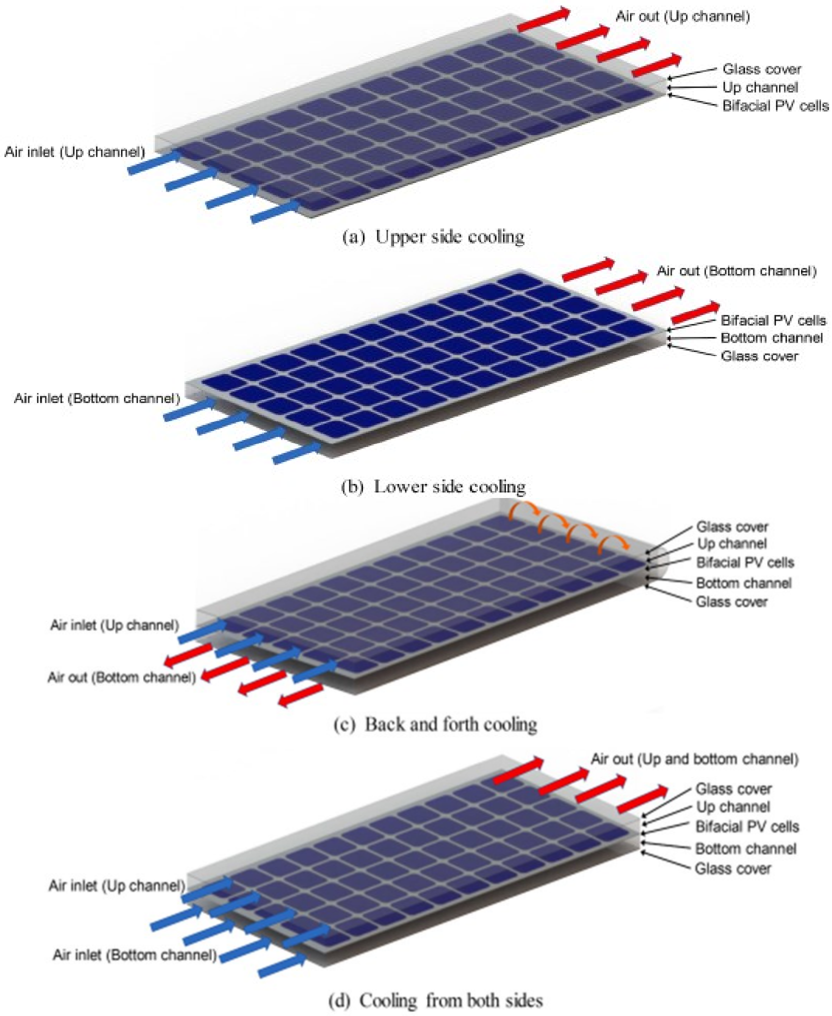


Figure 6. Various cooling techniques have been applied to BPV/T modules [47].

The performance of the passively air-cooled solar panel was studied using conventional continuous and segmented fins, as shown in Figure 7. The numerical study was first performed using the CFD software to optimize the fin width for a given fin spacing of 42 mm and a fin angle of 60° and varying the air flow directions. This was followed by an experimental study on a panel provided with (i) a continuous fin, (ii) a segmented fin with an optimized fin width of 20 mm, and (iii) a non-cooled panel. The segmented fin was found to decrease the panel temperature by 5-7 °C with an increase in the power yield of 2.96% compared with the non-cooled panel. The segmented fins performed well with varying airflow directions along with a smaller pressure drop, and the turbulence created further augmented the heat transfer [48]. CFD analysis of 14 different designs of the heat exchanger for cooling the solar panel was carried out by studying the effect of channel numbers, manifold width, location of inlet/exit ports, and tapered channels on the performance. An optimal design of a V-shaped heat exchanger was suggested to obtain a lower average temperature and non-uniformity in temperature, smaller hotspots, and lower pumping power. Based on experimental particle image velocimetry of the standard and tapered manifolds, it was found that the velocities were fairly uniform for the wide standard manifold; however, the presence of a taper at the exit enhanced the flow distribution [49].

Different PCMs, thermoelectric modules, and aluminum fin layouts, along with hybrid combinations, were experimentally tested to cool the photovoltaic module and to note the surface temperature of the PV panel and power output. The provision of fins was found to be the best choice [50].

The performance of the two-pass solar air heater coupled with the solar panel with different numbers of fins on the bottom side was tested. The panel acted as an absorber plate with a compound parabolic collector arrangement on the sides to focus solar radiation onto the panel. Air was forced over the top panel surface by a fan that flowed to the underside of the panel in the second pass. They reported an increase in the electrical efficiency of the panel of 28.7% for 24 fins [51]. One of the studies presented results for SPV cooling that utilized 1) aluminum heat sinks, 2) embedded heat pipes, 3) combined heat pipe and heat sink cooling, and 4) active water cooling. The most effective cooling was obtained using active water cooling. However, it was reported that active water cooling often may not be a practical choice, and embedded heat pipes and a medium-sized aluminum heat sink would be better [52]. A laboratory-scale hybrid system using an air-cooled PV panel in which air was forced on the rear side of the panel by a turbine located in the wind direction-oriented conic wind-collecting tunnel. Thus, solar panel cooling was achieved, along with the power developed by the wind turbine. The combined power output increased by 36% [53]. The study was carried out to assess the performance and payback of active (fan) and passive (chimney effect) air cooling of PV panels provided with a duct on the rear side, particularly focusing on hot and arid environments where the temperature of the cells may reach up to 80. A novel approach was suggested to evaluate PV cooling technologies that employ rapid laboratory testing with in situ experimental data. Active cooling delivered better performance, with the annual energy output increasing by 12.3%. However, considering the payback and ease, passive cooling would be a better option, with the annual energy output increasing by 9.58% [54]. This study was carried out to assess the computational model intended to cool solar panels with different arrangements of air-cooled channels. In this study, rectangular copper fins were employed. The goal of this study was to improve the heat transfer mechanism by varying the baseplate thickness, fin spacing, height, and thickness through a stepwise optimization procedure. The results observed that the PV cell models in air-cooled channel configurations with and without fins were 40.28°C and 42.58°C, respectively [55]. The article was published as a review of a number of recent studies on PV cooling techniques, including passive, active, and mixed cooling. It was discovered that PV cooling faces several significant obstacles that need to be addressed in subsequent research, such as expense, upkeep needs, energy usage (particularly for active cooling techniques), and performance in harsh environments [56]. Table 2 provides a brief overview of the few recent studies pertaining to air cooling, apart from those discussed in this section.

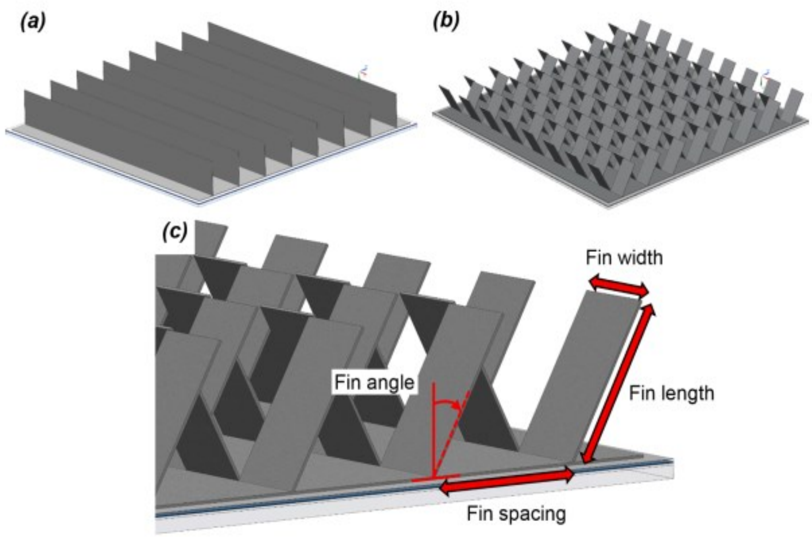


Figure 7. PV cooling system, (a) conventional heat sink, (b) proposed heat sink, and (c) fin parameters [48]

Table 2. Summary of literature review on air cooling of PV panels.

Authors	Mode of investigation	Cooling mediums	Surface temperature of PV panel reduced up to	Electrical efficiency of PV panel achieved up to	Key features
Srithar et al [57] [2025]	Experimental investigation	Air cooled with baffles	11 °C	9.8%	PV panels with two distinct baffle configurations were contrasted with a standard PV panel.
Ibrahim et al. [58] [2022]	simulation study using CFD	Air cooled with fins	10.67 °C	-	Traditional fins, circular fins, and triangle perforated/dimpled fins were used to cool the PV.
Ali et al. [59] [2025]	Experimental investigation	Dual side air cooling	24-47 °C	24%	Dual-cooling approach for PV panels to improve SPV panel performance when contaminated by bird droppings
Nabil et al. [60] [2024]	Experimental investigation	Air cooled	16 °C	25.29%	Three PV cooling methods were studied (1) marble-based evaporative cooling, (2) fan-assisted airflow evaporative cooling employing palm fibres, and (3) thermoelectric cooler modules.
Masalha et al. [61] [2024]	Experimental investigation	Air and water cooled	24 °C	15.20%	A PV cooling system using air and water spray was suggested and investigated.

2.2. Water cooling

The literature discussed in this section pertains to the use of water as a working fluid. Water may simply flow over the top and/or back surface of the panel, or it may be circulated through the tubes or channels provided on the back side of the PV modules. In one such experimental study, the authors reported a panel that was cooled by allowing water to flow over the top surface, whereas the bottom of the panel was cooled by employing a cotton wick mesh that maintained the downward flow of water by capillary action. The output power and electrical efficiency of the panel increased by 30.3% and 11.9%, respectively [62]. The experiment was conducted in Nagpur [21°N, 79°E], India, on a special formation of an inverted trapezoidal flume shaped photovoltaic system that produced both electrical energy and thermal energy simultaneously, as shown in Figure 8. One 40 W PV module covered the top surfaces of the system, while both lateral surfaces were partially covered with 10 W PV modules. The remaining half of the lateral surfaces were used as the thermal collectors. Water-cooling channels were attached to the rear surfaces of all three PV modules. Plane mirror reflectors were used on all the sides to maximize the output. The electrical efficiency and the overall efficiency that considered both electrical and thermal efficiencies were found to be maximum when both water cooling and reflectors were used [63]. Water was allowed to trickle through the number of holes in the top header pipe over the top surface of the PV panel. The experiment was conducted on a photovoltaic system used for water pumping for irrigation purposes. They showed that the power output would increase due to evaporative cooling of water and due to increasing incident solar radiation on the PV module due to solar beam refraction in the water layer. They observed an increase in the power output of 15% under peak radiation conditions. The authors also predicted the long-term performance using the ambient temperature and radiation data at the site and concluded that there would be a 5% increase in the energy delivered by the system during the dry and warm seasons [64].

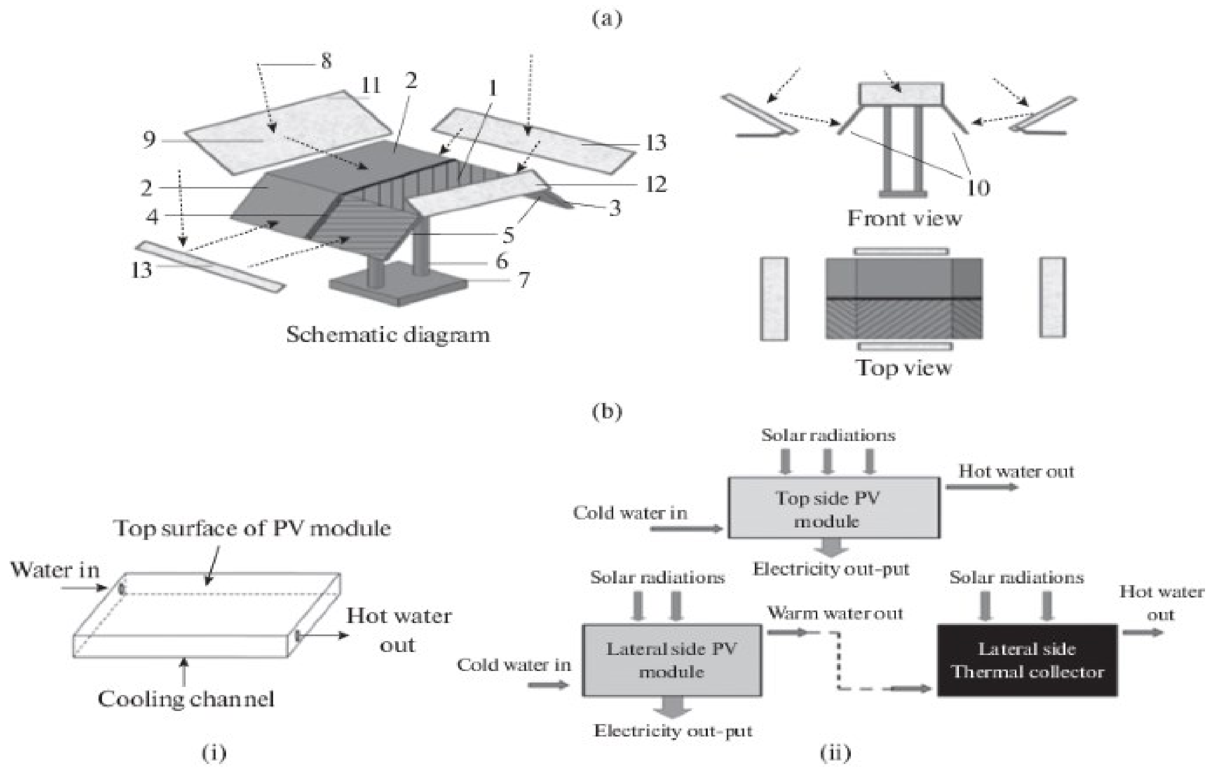


Figure 8. (a) Experimental setup and views. Legends: (1) glazing cover; (2) PV modules; (3) thermal collectors; (4) thermal separator; (5) cooling channel with glass wool insulation; (6) supporting columns; (7) base; (8) incoming solar radiation; (9) reflected radiation; (10) lateral surface; (11) south-facing mirror; (12) north-facing mirror; and (13) lateral side mirrors. (b)Mechanism of heat extraction from PV module. [63]

Water was allowed to form a film over the top surface of the panel by employing a number of nozzles, which kept the solar panel temperature closer to the ambient temperature. Apart from keeping the surface clean, the reflection of radiation was found to be reduced by 2–3.6%, and the power output increased by 10.3%. A reduction in temperature was observed up to 22°C. Considering the power consumed by the pump, the net power output returned a surplus of 8-9% [65]. An innovative cooling box was proposed to operate as a thermal collector attached to the rear side of the PV system, as shown in Figure 9. The results of the simulation study for different inlet mass flow rates and temperatures were simulated under the normal operating cell temperature conditions. The investigation included the temperature distribution and the average temperature of the photovoltaic module layers. For the optimum mass flow rate of 0.014 kg/s and an inlet temperature of 15°C, the PV module delivered electrical and thermal efficiencies of 17.79% and 76.13%, respectively. Heated water can be used for domestic purposes or for heat pumps and space heating [66]. Floating PV systems may be a better option in view of the large land area requirements for solar power plants. A thermosiphon-based passive heat exchanger was proposed to cool the PV panel, and its performance was compared with that of its conventional land-based and floating counterparts. Experimentation showed a 4.52% increase in power output in the case of a conventional floating PV system compared to land installation. Furthermore, the use of a thermosiphon heat exchanger, as depicted in Figure 10, was found to increase the power output by 7.86% compared to land installation, thus producing a 3.34% surplus power relative to the conventional floating system [67]

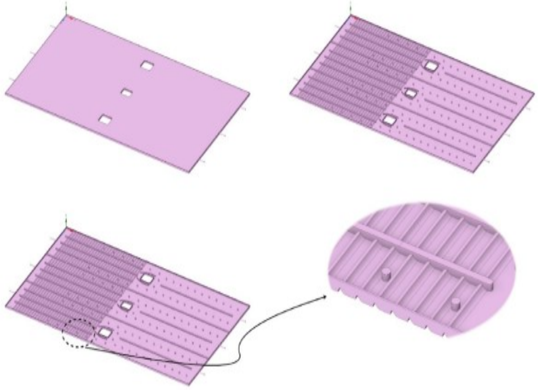


Figure 9. Cooling box design [66]

Figure 10. Floating PV experimental configuration of (a) thermosiphon-floating PV system and (b) bottom view of solar module attached to heat-absorber pipes [67].

The electrical and thermal performances of a PV-powered reverse osmosis (RO) water desalination system were assessed. Brine rejected by the RO system was used to cool the PV panel by spraying it through holes in the header pipe over the top surface. Heated brine was used to preheat the feedwater to the RO system, thus increasing its productivity. A maximum 20% increase in the electrical efficiency of the PV panels was observed. However, the corrosive effect of brine has been studied [68]. A photovoltaic-thermal system with a serpentine coil-configured sheet and tube thermal absorber on the rear side was tested for its electrical and thermal performance. Plain water and water nanofluid (copper oxide-based) were passed through the absorber. The electrical efficiency was found to increase by 12.32% and 35.67% for plain water and water nanofluid, respectively, compared to the uncooled PV panel [69]. A validated mathematical model was proposed to study the dynamic thermal behavior of the PV-thermal water-based collector, where the water tubes were bonded on the rear side of the PV panel. The water in the tank was cooled in the night by radiative cooling when it passed through the collector tubes and was used the next day to cool the panel. The performance of this system was compared with that of the same PV/T collector, where radiative cooling at night was not employed. The monthly gain in electrical energy is noticed to be 5.5%–6.15% when cooling is used [70]. To decrease the consumption of water sprayed over the top surface of the PV panel with the arrangement shown in Figure 11, the cooling performance in the case of the pulsed spray was compared with that of the steady spray. Compared with the non-cooled panel, it was found that the maximum power output of the panel increased by 33.3%, 27.7%, and 25.9% for steady spray, pulsed spray with 1 DC (duty cycle, the ratio of on-time to off-time in a cycle), and pulsed-spray with 0.2 DC. The water consumption was reduced to one-ninth in pulsed-spray with DC = 0.2 compared with steady flow [71]. Similar experimental studies reported a significant improvement in performance when water was sprayed over the front surface or on the front surface, as well as the rear surfaces [72][73]. An experimental investigation was carried out on the panel performance of a PV panel fitted with V-shaped aluminum cooling channels at its back surface as a passive technique. Water was allowed to flow through these channels to cool the panel. All of the selected flow rates employed in the study, which range from 0.3 LPM to 0.6 LPM in increments of 0.1 LPM, tend to increase the panel's output. A temperature reduction of roughly 12.7°C is observed for the volume flow rate of 0.3 LPM, which results in a decrease of approximately 21.6% when compared to the simple PV panel without cooling arrangements [74]. Two identical 100-W PV panels made up the PV system, and an automated water-cooling system was constructed. According to the experimental findings, a temperature reduction of up to 14.6 K could be accomplished using the water technique that was chosen. The cooling of the PV panel increases the related power production by up to 12% [75]. A few more recent investigations reported by various researchers regarding water as a medium for PV panel cooling using different configurations for improving electrical efficiency are listed in Table 3.

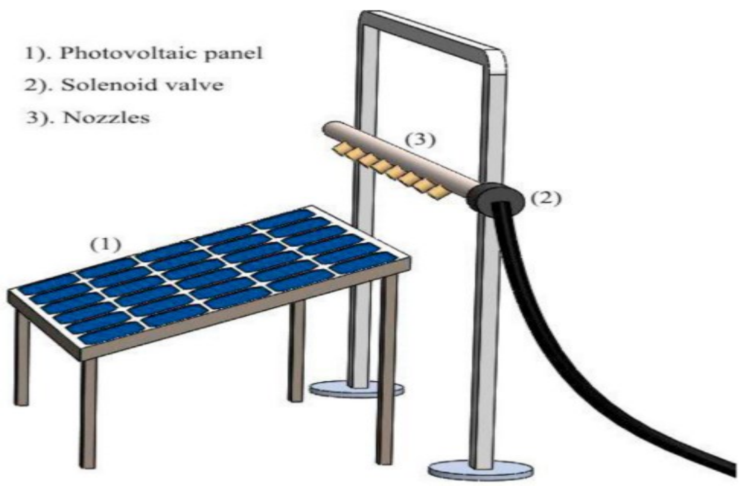


Figure 11. PV panel schematic view with spray-cooling system [71]

2.3. Phase change materials

This section elaborates on the different phase change materials used as cooling agents to extract heat from PV panels to enhance the electrical efficiency. The heat stored in phase-change materials (PCM) is utilized for various applications. A review of the literature pertaining to the use of PCM in photovoltaic panel cooling was published in May, 2021. The effects of the physical properties of the PCM, ambient conditions, and design of the PCM encapsulation were included in the numerical and experimental analyses. The typically low thermal conductivity of phase change material from 0.16 to 0.25 W/mK, could be enhanced by mixing nanoparticles and metallic foam into these materials [29]. Another study, published in July 2017, focused on the development of next-generation PCMs through the enhancement of thermophysical properties, such as thermal conductivity, latent heat of fusion, and sensible heat. This paper presents a review of research updates on thermal energy storage and efficient heat transfer [76]. Simulations were performed on three PCM materials, viz., paraffin wax, gallium, and sodium nitrate (metal-based and organic and inorganic compound-based) employed for thermal storage using the enthalpy-porosity formulation methodology of ANSYS-Fluent software. The melting and heat-transfer behavior, availability, and cost were compared. It was concluded that although sodium nitrate is sluggish in its response, ways to enhance its efficiency should be explored in view of its availability and cost [77]. Experimental work was reported on the thermal management of a PV system using a PCM material, polyethylene glycol 1000, which was filled in eight aluminum rectangular boxes in contact with the rear side of the panel. The results showed that the PV module temperature decreased by 15°C when the solar radiation was 800 W/m^2, whereas its efficiency found to increase by 8% [78]. A mathematical model validated by experimental measurements was used to study the effect of climatic conditions on the performance of PV panels integrated with PCM. Changes in temperature and power generation over time were computed for various types of climates.

Table 3. Literature review summary for water cooling of PV panels

Authors	Mode of investigation	Cooling medium	Surface temperature of PV panel reduced up to	Electrical efficiency of PV panel achieved up to	Key Features
Kargaran et al. [79] [2024]	Experimental investigation	Nano particle and Water cooling	-	Electrical efficiency increased by 12.07%	The research was carried out on different nano fluid with different concentration.
Sornek et al. [80] [2023]	Experimental investigation	Water cooling	27-55 ℃	Electrical efficiency increased by 1.2-13%	A technique for cooling photovoltaic panels using direct water has been created and tested.
Lotfi et al. [81] [2022]	Experimental investigation	Water, pure Ethylene-Glycol (EG) and mixture of water/EG cooling	37.3 ℃	Electrical efficiency increased by 6.84%	Experimental research was done on three different kinds of cooling fluids: pure water, pure ethylene glycol (EG), and a mixture of water and EG in the same ratio.
Satpute et al. [82] [2022]	Computational analysis using CFD-FLUENT	Water cooling	44.2 ℃	Electrical efficiency improved by 11.97%	Several absorber designs for PV and PVT systems were investigated that include zigzag, spiral circular, and serpentine semi-circular.
Aboushi et al. [83] [2022]	Experimental investigation	Water and Nano particle cooling	Temperature reduced by 4 ℃	Electrical efficiency improved by 11.97%	The PV module's performance was enhanced by the use of finned surface and water as natural convection.

They concluded that (i) climates with less variation in the ambient temperature were more suitable for PCM integration, where power generation increased by 9.7%. However, for a climate with a large variation in temperature, the increase in power was observed to be 6.6%, (ii) the performance of PCM systems was better in warm climates compared to cold ones, (iii) PCM would be effective in climates with low wind speed and high solar radiation, and also when wind flow was across the PV [84]. To improve the performance of the PCM, owing to its low thermal conductivity, triangular metal fins were inserted into the aluminum housing carrying the PCM. However, the thermal regulation period decreased as the volume of the PCM was replaced by the metal mass. Therefore, two PCMs, paraffin wax RT27 and RT21, with melting points of 27 and 21°C, respectively, were used in the same housing with fins to enhance the thermal regulation effect, and the highest temperature reduction was observed [85]. Indoor and outdoor tests were conducted on a PV panel along with reflectors on the east and west sides in the form of a V-trough, which enhanced the solar insolation. The PCM, paraffin wax, embedded with aluminum lathe turnings, was placed in a 6 cm thick aluminium housing in contact with the rear side of the PV panel for cooling. A desirable drop in temperature from 78°C to 62°C was observed, along with an enhancement of 1.55 times in the output power over the day [86].

An experimental investigation of an inorganic PCM (calcium chloride hexahydrate), 4 cm thick, placed in transparent acrylic boxes attached to the back of the PV panel with a solar-tracking arrangement was presented. The melting dynamics of the PCM were observed to differ from those of the fixed panels. Furthermore, the enhancement in efficiency and reduction in temperature, an average over the day, were observed to be 4.6% and 9.1°C, respectively, when compared to the non-cooled panel [87].

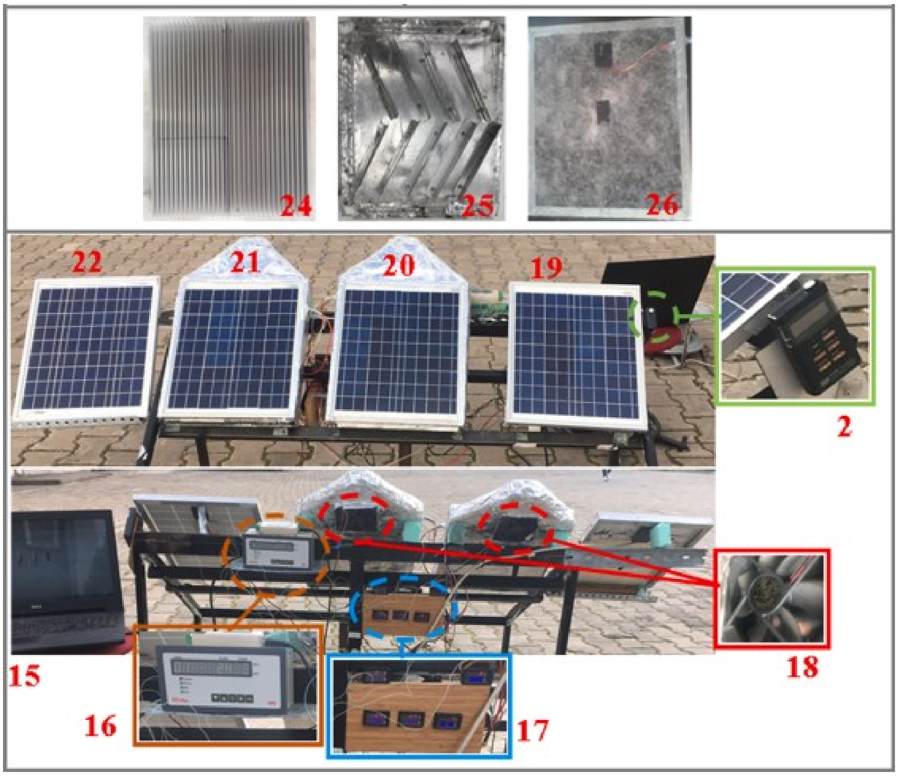
The simultaneous use of PCM cooling for the PV panel along with naturally circulated water in the channel below the PCM holder was tested by considering four cases, viz., (i) continuous flow of water from the bottom to the top of the channel from the beginning to the end of the experiment, (ii) similar to case (i) with water flow allowed after achieving a Tedlar surface temperature of approximately 45°C, while cases (iii) and (iv) were repetitions of (i) and (ii) above, with only the change in direction of water flow from the top to the bottom of the channel. Commercially available organic material OM 35 was used as the PCM, and its performance was compared with that of a non-cooled PV panel. Cases (i) and (iii) with a continuous supply of water from the beginning to the end performed better than cases (ii) and (iv). Furthermore, case (iii), with the top-to-bottom water-cooling technique, showed the best performance with increases in average electricity generation, electrical efficiency, power enhancement percentage, average temperature reduction, maximum overall exergy output, and exergy efficiency of 11.92%, 12.4%, 13.54%, 5.4°C, 26.07%, and 8.08%, respectively [88]. A paraffin wax (PCM) and steel foam mixture was applied on the back side of the panel, which was covered with a heat sink with (i) inclined fins and (ii) flat fins that were cooled using forced air flow, as shown in Figure 12. The performance of these two arrangements was compared with that of the reference PV panel. The surface temperatures for the first and second arrangements were found to decrease by 12.23% and 21.67%, respectively, compared to the reference panel. The electrical efficiencies were observed to be 5.09% and 6.18% for the first and second arrangements, respectively, as opposed to 4.38% for the reference panel [89]. The performance of the three cooling methods, that is, PCM, thermoelectric module (TEM), and aluminum fins, was studied experimentally along with a cost and efficiency analysis. Two different PCMs, namely Biphenyl and Calcium chloride hexahydrate, were tested. It was found that biphenyl, whose melting temperature was above the PV panel surface temperature, had a negative effect on the panel output power. Further, it was noticed that, under the same environmental conditions, the power output for the finned system was 47.88 W, while that for the thermoelectric module, calcium chloride hexahydrate and finned system, and hybrid system (all three together) were 45.87 W, 44.36 W and 44.26 W, respectively. It has been advocated that the use of aluminum fins is the most economical and delivers the highest efficiency and output power [50].

The PCM and the water container together concluded that in the second case, the water carried heat effectively from the molten PCM, which improved the performance and produced hot water for other applications. The PCM container was taken to be 50 mm thick, while the water container thickness was varied, and it was found that a water container thickness of 30 mm was optimal. Further, for the system orientations of 30° and 90°, the reduction in temperature was 5.88% and 1.36%, while the corresponding increase in efficiency was 14.93% and 1.35%, respectively [90].

A eutectic mixture of 70% calcium chloride hexahydrate and 30% iron chloride hexahydrate was

used as the PCM coolant to study the performance of the PV panel both experimentally and numerically. The temperature of the panel was 9 °C lower and the electrical power was 96.55 Whr. higher for the PCM-cooled panel compared to that without cooling [91]. Paraffin wax was used as the PCM, along with different numbers of metallic fins, to improve its thermal conductivity. The finned PCM was observed to improve the electrical efficiency of the panel by 5.39%, while the reduction in temperature was 15°C compared to the panel without cooling [12].
A numerical model validated using available experimental observations from the literature was used to predict the performance of the concentrated A numerical study that addressed the cooling of a PV panel attached to a PCM container and later with a

PV-PCM system. The effect of a change in the orientation angle from – 45° to 90° with an interval of 45° was examined with a concentration ratio of 5 and 20, while the thickness of the PCM was taken as 50 and 200 mm. An inclination of 45° was found to deliver better performance along with enhanced uniformity in solar cell temperature [92]. A mathematical model was developed to obtain the optimum depth of the PCM container that cooled the PV panels. They suggested that the optimum depth for different operating conditions depends on the ambient temperature, melting temperature of the PCM, wind direction, and velocity [93].



2.TES1333R solar power meter	20. PV/T+PCM/Sf+Hsi collector
15.Computer	21. PV/T+PCM/Sf+Hsf collector
16.Elimko E-680 data logger	22. Cooling fan power supplyPV module
17.Resistive load	24. Flat fin heat sink
18.Yate Loon GPD12SM-12 12V DC fans	25. Inclined fin heat sink
19. PV module	26. Paraffin and steel foam mixture filled backside of PV/T collectors

Figure 12. Experimental setup visualization [89]

The copper absorber plate of the collector filled with fatty acid (phase transition temperature of 37°C) as the PCM inserted with fins was integrated at the back of the PV panel. Water was allowed to flow through the serpentine copper tubes attached to the bottom of the PCM collector to carry away the heat for temperature regulation once the predetermined temperature was reached. They used different temperature regulation strategies to optimize the performance of the above PV/T-PCM system with the surface temperature set to 45°C or 50°C. They observed a regulation temperature of 45°C to deliver better system performance. The average electric efficiency was found to increase by 6.4 to 7.5%, whereas the increase in thermal efficiency was 7.5 to 8.4% depending on the operating conditions [94][95]. An economic analysis of the PCM cooling of PV panels using standard climate data for different regions on Earth has been reported. It was shown that it would be most beneficial in regions with high insolation and little intra-annual variability in the climate [96]. A microencapsulated phase-change material (MPCM) slurry was used instead of a solid PCM to cool the PV panel. An experimental study found that the effective increase in the average electrical efficiency and the maximum thermal efficiency were 0.8% and 13.5%, respectively [97]. Experimental investigation of a PV panel cooled using a PCM with a honeycomb-structured aluminum metal matrix to improve its thermal conductivity. The temperature was reduced by 11.1%, while the conversion efficiency was improved by 8.6% [98]. The study included a thorough assessment of previous research, proper categorization, and critical evaluation of four different PCM-based cooling systems: hybrid, finned, composite, and pure PCM systems [99]. A Phase Change Material (PCM)-based cooling technique in conjunction with aluminum fins lowers the PV panel's temperature. Using inclination angles of 300, 450, and 600, the experimental results indicated that the PV panel efficiency increased by 6.85%, 6.82%, and 4.2%, respectively [100]. The study's implementation involved adjusting the tilt angle of the PV panels to 15°, 20°, 25°, and 30 °while using PCM thicknesses of 1, 2, and 3 cm. For PCM thicknesses of 1, 2, and 3 cm, the temperatures at the top of the panel were 17.1%, 15.7%, and 13.2% higher than those at the bottom, respectively [101]. Table 4 summarizes some of the recently reported findings for the PCM cooling of PV panels.

2.4. Phase change materials with nano particles

This section deals with the literature in which nanoparticles are mixed with PCM or water to enhance the thermal properties of fluids. The most commonly used nanofluids for experimentation are Al_2O_3, CuO, ZnO, and SiO_2. The review paper addressing the use of nanofluids to improve the performance of hybrid PV/T systems covered the reported experimental, numerical, and combined studies and underlined the increase in thermal and electrical efficiency, heat transfer characteristics, and exergy, as shown in Figure 13 [102].

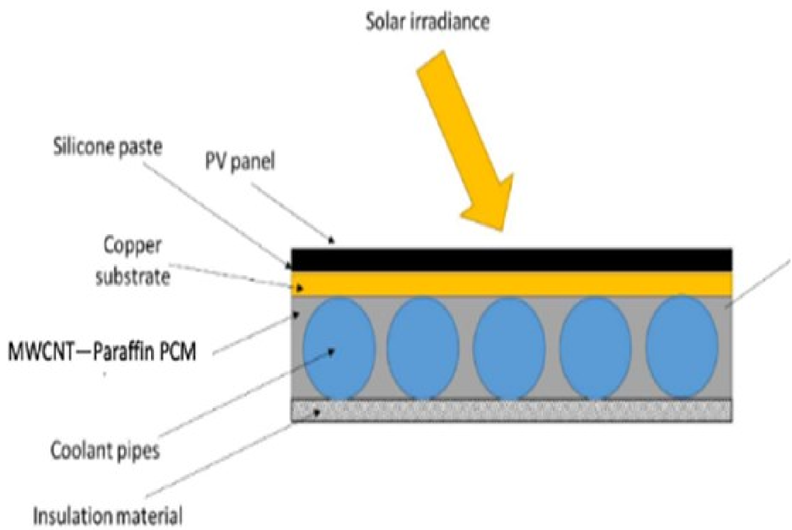


Figure 13. Mixture of PCM and nanoparticle cooling [102]

An experimental test rig was fabricated to study the thermal behavior of a PV/PCM system using RT35HC as the PCM and Al_2O_3 as the nanoparticles. In addition, cylindrical fins were used to enhance the heat transfer. It was observed that the surface temperature of a heated aluminum plate that simulated the panel reduced by 20 to 46.3% by using PCM only for different fin sizes, and the reduction in temperature for PCM along with nanoparticles was 52.3% [103]. A study was performed on latent heat storage to note the effect of adding Al_2O_3 and TiO_2 nanoparticles in a PCM $NaNO_3$:KNO_3 (60:40). The concentrations of nanoparticles in the PCM were chosen to be 1%, 3%, and 5% by mass. The latent heat capacity increases at a concentration of 3%. Further, characterization studies showed that TiO_2 would be preferred for the PCM used in view of the improvement in thermo-physical properties and heat storage characteristics [104]. The literature review published in 2018 focused on methods for improving the thermal conductivity of PCMs in a thermal energy storage. It was concluded that the addition of fillers is a more effective method to enhance thermal conductivity, in general, and carbon-based material additives in particular [105].
Another review explored the use of carbon-based nanostructures (CNs) to prepare nanocomposites with PCMs using the encapsulation method. The features that lead to the improvement in the thermal properties of PCM/CN have been identified [106]. Different machine learning (ML) approaches have been studied to simulate and predict the performance of PV/T systems using water-nanoparticle coolants. The adaptive neuro-fuzzy inference system (ANFIS) was found to be the best method among the methods studied, including artificial neural networks and least-squares support vector regression [107].

Table 4. Literature review summary for PCM cooling of PV panels

Authors	Mode of investigation	Cooling mediums	Surface temperature of PV panel reduced up to	Electrical efficiency of PV panel achieved up to	Key features
Awad et al. [108] [2022]	Experimental investigation	PCM + Fins and Nano Particles (RT25) cooling	-	overall efficiency improved by 40.59%	By using fins and phase-change materials together with nanoscale fluids to increase electrical efficiency.
Alinia et al. [109] [2021]	Numerical investigation	PCM + Fins (RT35HC) cooling	-	Electrical efficiency increased by 16.46%	A TEG was incorporated into the PV module, and the PV cooling system is made out of a finned duct that is filled with paraffin and reinforced with SWCNT nanoparticles, which increase the paraffin's thermal characteristics and enable more efficient heat dissipation.
Badgujar et al. [110] [2024]	Experimental investigation	PCM (Paraffin Wax) Cooling	PV panel temperature reduced with 11.5 ℃	Electrical efficiency increased by 3.36%	The paraffin wax used as PCM cooled PV panel.
Bhakre et al. [111] [2022]	Experimental investigation	PCM (PEG 500) cooling	PV panel temperature decreased by 14.08%	Electrical efficiency increased by 8.87 %	The phase change materials Polyethylene Glycol 1500 provided on back side of photovoltaic panel and observed temperature performance and electrical efficiency.
Biwole et al. [112] [2011]	Analyzed using CFD software	PCM (RT25)	PV panel temperature decreased up to 34.9 ℃	-	The use of phase-change materials (PCM) to keep the panels' temperature near ambient is examined in the current study.

A comprehensive review of different ML techniques was presented that covered every aspect of PV systems, including control, islanding detection, management, fault detection and diagnosis, forecasting irradiance and power generation, sizing, and site adaptation. In addition, resources were reported to obtain open datasets, source code, and simulation environments that would be useful for testing ML algorithms [113]. A numerical simulation study addressed the use of SiC and Al_2O_3 nanoparticles mixed with water that passed through a wide microchannel heat sink underside the concentrator PV panel. The effects of the volume fractions of nanoparticles and Reynolds number of flow on the performance of the panel were studied. At a given solar concentration ratio of 20, the reduction in temperature of the panel for 4% SiC-water nanofluid, when compared with plain water, was in the range from 8°C to 3°C for Reynold number changing from 12.5 to 250 [114].

The comparative performance of a plain PV panel and a PV thermal (PVT) collector was reported when different nanofluids, that is, SiO_2, TiO_2 and SiC, along with water, were employed in the PVT system. SiC nanofluid delivered the highest combined photovoltaic thermal (PVT) efficiency of 81.73% and PVT electrical efficiency of 13.52%, followed by TiO_2, SiO_2, and plain water [115].

The review concentrated on using mono (NFs) and hybrid (NFs) materials to enhance PV/T thermal and electrical performance while considering operating factors, nanoparticle type, concentration, and PV/T design. Bi-fluids have significantly increased PV/T electrical and thermal efficiencies by up to 26% and 85%, respectively, while NFs demonstrated increases of 24% and 82%, respectively [116].

Three conventional polycrystalline solar panels were used in the experimental study, which was conducted concurrently, simultaneously, and under identical meteorological conditions. Using water and aluminum oxide nanofluid, the electrical and thermal performances of a photovoltaic thermal (PVT) system integrated with a serpentine coil-configured sheet and a plate thermal absorber setup were assessed. The panel temperature is lowered by 10.0°C and 20.0°C at noon by water and nanofluid cooling, respectively [117]. This experimental study investigated the cooling of photovoltaic (PV) panels using nanofluids containing metallic (calcium carbonate, $CaCO_3$) and non-metallic (ferro-magnetite, Fe3O_4) particles. The average cell surface temperature was significantly lowered by using $CaCO_3$ and Fe_3O_4 nanofluids in comparison to the uncooled and water-cooled systems [118]. Solar energy is used to heat the water, and the heated water is used to charge the PCM in the absorber tube, and the same PCM discharges to heat the water. The analysis was performed using CFD software [119]. Table 5 lists other recent research findings regarding a mixture of water and nanoparticles used to cool the photovoltaic panel.

Table 5. Literature review summary of nanoparticle cooling of PV panels

Authors	Mode of investigation	Cooling mediums	Surface temperature of PV panel reduced up to	Electrical efficiency of PV panel achieved up to	Key features
Merzah et al. [120] [2024]	Numerical investigation	PCM+Nanofluids (Al_2O_3 ,CuO and TiO_2).	PV panel temperature dropped up to 49.89 ℃	PV panel electrical efficiency rise 9.26%	Phase change materials and nanoparticles were used in the current study to investigate PV passive cooling techniques.
Pereira et al. [121] [2023]	Review	PCM + Nano-Particles.	-	-	The study examined nano-enhanced phase-change materials for use in energy conversion and harvesting.
Sangeetha et al. [122] [2020]	Numerical investigation	Nanofluid (Al_2O3, CuO, and multiwall carbon nanotube) (MWCNT)	Reduced the cell temperature by 19%.	Average electrical efficiency increased by 60%	Multiwall carbon nanotubes gave better results than $Al2O_3$ and CuO materials.
Sheik et al. [123] [2022]	Review	mono (NFs) and hybrid (NFs)	-	Average electrical efficiency increased by 24%	The review on effect of using PCM and nano PCM (NPCM) in cooling PV cells
Masalha et al [124] [2025]	Experimental and Numerical investigation	Porous media cooling	PV surface temperature reduced by 35.7%.	power output increased by 9.4 %	The study aimed to determine the best cooling parameters (such as coolant type, flow rate, and porosity size), assess the effects of cooling techniques utilising porous media, and offer insights into cooling channel designs that optimise PV panel performance.

2.5 Evaporative cooling

This section discusses evaporative cooling of PV panels using different absorbent materials. A clay layer was prepared on the rear side of the photovoltaic panel. Clay soaked with water permitted a reduction in the photovoltaic panel temperature. The results showed that the output power increased by 19.1% when a layer of clay was added [125]. Several spirally wound cotton wicks were attached to the rear side of the panel, which absorbed water by capillary action from the bottles kept below, as shown in Figure 14. The panel temperature was reduced by 30%, whereas the conversion efficiency increased by 10.4% with a passive evaporative cooling arrangement with regular water. CuO/water and Al_2O_3/water nanofluids were also tested; however, the reduction in temperature was only 11% and 17%, respectively. The deteriorated performance of nanofluids was attributed to the weakening of capillary action owing to the adherence of nanoparticles to the wick fibers [126].

A piece of cloth was attached to the rear side of the panel and was wetted by supplying water from the tank by gravity through the rubber pipes in contact with the cloth. Such evaporative cooling was found to increase the electrical efficiency by 14% along with a 20°C reduction in the panel temperature compared to a non-cooled panel [127]. Air was forced through the duct at the bottom of the PV panel, and the cloth wetted with water was attached to the lower surface of the duct instead of the panel. Thus, the lowering of air temperature due to evaporative cooling in the duct resulted in a 5% improvement in power from the panel, while its surface temperature was reduced by 10°C [21]. The photovoltaic panel cooled with cotton wicks attached to the rear side, which was soaked in water, is shown in Figure 15. The drop in the surface temperature was observed to be 22%, with a corresponding increase in the power yield and efficiency. The experiment was conducted on a PV panel that employed a pad wetted with water attached to the back surface, forcing air through the covering channel. The efficiency of the panel was enhanced by 10% [128]. The lower surface of the duct attached to the rear side of the panel was covered with a piece of cloth on which water was allowed to flow. Air was forced through the duct in the same direction as water. A physical model based on heat and mass transfer was developed for the above system to study the effects of geometrical parameters such as the air flow rate, temperature, and humidity of air. It was predicted that the temperature would be reduced by approximately 6°C under the chosen input conditions [129]. The PV panel was provided with a pin-finned heat sink on the back side along with a wood wool pad, which was kept moist using water. This novel cooling concept resulted in a 26.05% reduction in the cell temperature. The efficiency and power yield were increased by approximately 31.5% and 32.7%, respectively [22].

The fins at the back of the PV panel and the wick structure between the fins were used for cooling. The temperature reduction and corresponding increase in electrical efficiency were 12% and 14%, respectively [130]. The front surface of the PV panel was cooled by allowing water to flow over the top surface, whereas a wetted cotton wick mesh was used on the rear. The common perforated header pipe at the top edge of the panel provided water supply from the overhead tank. The average temperature decreased from 59.27°C to 35.72°C along with 11.9% increase in electrical efficiency [62]. The experiment was carried out on evaporative cooling, in which pads were utilized to chill the two modified PV systems by varying the coolant flow rate. According to the results, the average daily power increment ratio (PIR) for CCPV varies from 6.7% to 12% depending on the climate, whereas the PIR for CPV ranges from 4.7% to 7.4% [131].

In one of the studies, a review was conducted on several uses of solar-assisted liquid-desiccant cooling in conjunction with evaporative air conditioning in various climates for energy saving. The fundamentals of a hybrid solar liquid desiccant system that uses both direct and indirect evaporative cooling are explained. In, research article developments for the liquid desiccant air-conditioning systems were presented [132]. Research conducted by many researchers on the use of solar energy in hybrid space cooling using solid desiccant and vapor compression has been compiled. This study examined the use of solar energy as a renewable regeneration heat source in heat-driven solid desiccant-based hybrid cooling systems [133]. Table 6 summarizes the findings of a few recent studies that have employed some form of evaporative cooling.

Table 6. Literature review summary for evaporative cooling of PV panels

Authors	Mode of investigation	Cooling mediums	Surface temperature of PV panel reduced up to	Electrical efficiency	Key features
Siabdallah et al. [134] [2014]	Experimental investigation	Evaporative (Water-Wet Jute Fabric) cooling	PV panel temperature reduced by 23 ℃	Increment in efficiency by 1.3%	The experimentation was conducted on PV panel backside covered with jute fabric that is constantly wetted with water as a cooling mechanism
Jaffar et al. [135] [2024]	Experimental investigation	Evaporative cooling	PV panel temperature reduced by 25 ℃	PV panel electrical efficiency increased by 9.3%	Two methods of solar thermal collectors were employed in this experiment: one that integrated the PV module with a forced air duct, and the other that included a direct evaporative cooling device
Li et al. [136] [2024]	Experimental investigation	Evaporative cooling	PV panel temperature reduced by 10 ℃	Electrical efficiency increased by 13%	The novel and adaptable method of cooling PV panels was illustrated that used an efficient cooling component based on sorption-based atmospheric water harvesting.
Wankhede et al. [137] [2023]	Experimental investigation	Evaporative cooling	-	-	Presented the evaluation of sustainable passive cooling methods for solar (PV) panels through experimentation and comparison
Mahmood et al. [138] [2024]	Simulation	Evaporative cooling	PV panel temperature reduced by 15 %	Increased in electrical efficiency by 17%	Using TRNSYS software, a photovoltaic evaporative system was aided with groundwater in a typical desert area.

2.6 Radiative cooling

Radiative cooling of PV modules is a passive cooling method that employs spectrally selective coatings to absorb and emit radiation. The major advantage of radiative cooling is that it is a passive cooling method that does not require any electrical or mechanical energy or additional arrangement and/or attachments. This would be the only option for a cooling mechanism to improve the performance of solar cells, particularly in space applications. A study on radiative cooling reported that it is more effective than convection and conduction, particularly at high temperatures. Three different cooling designs employing a concentrated PV system with gallium antimonide solar cells integrated with soda-lime glass-based radiative coolers were experimentally and numerically investigated. The designs included a flat-plate heat sink in a sealed chamber, a flat-plate heat sink in an open chamber, and a finned heat sink in an open chamber that was tested for heat loads from 6 to 100 W. It was noticed that for a heat load of approximately 6 W, combined convective and radiative cooling brought about a 5°C to 36°C reduction in temperature and an 8% to 27% rise in V_{OC}. The contribution of radiative cooling would be significantly less with better convective cooling, which was found to be approximately 25% at best [139]. In one of the studies, a mathematical model that considered the effect of different climatic conditions and emissivity spectrum on the surface temperature was reported. It was found that an emissivity of 1.0 (i.e., thermal black body) over the entire thermal radiation spectrum would be the most desirable proposition.

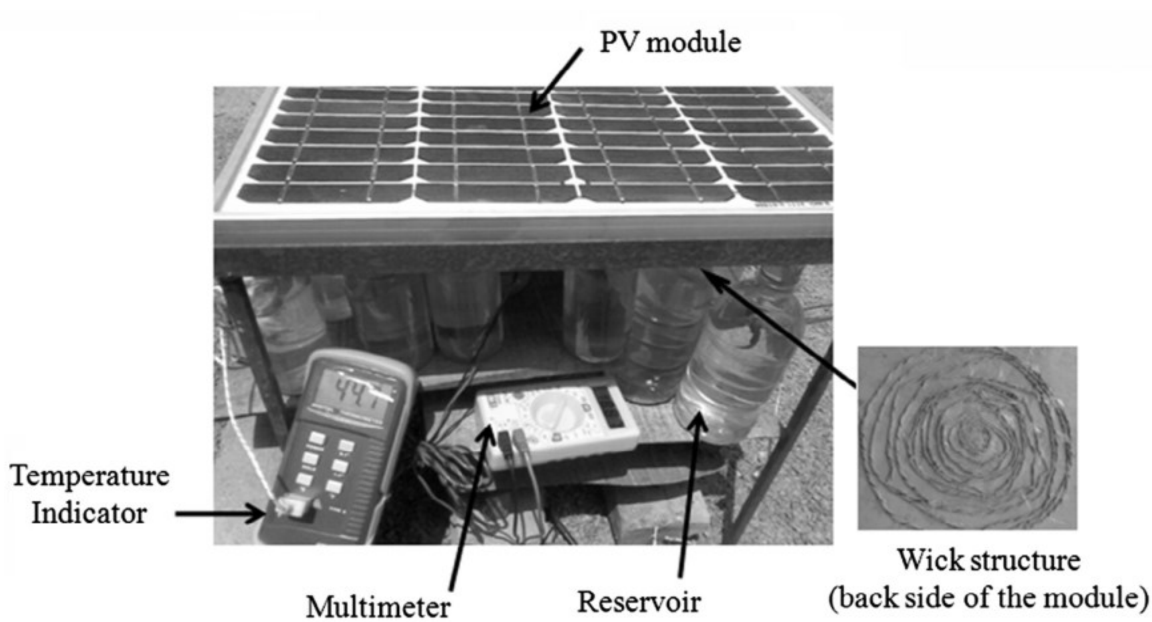
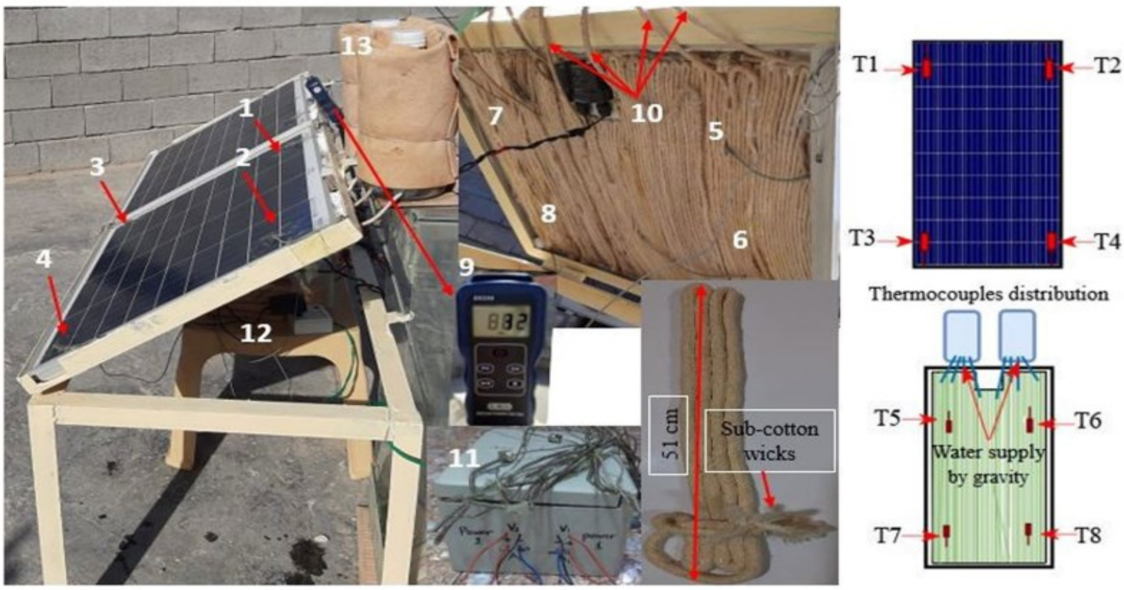


Figure 14. PV, with evaporation [126]



Part No.	Descriptions	Part No.	Descriptions
1-4	Thermocouples	11	Data logger system
5–8	Backside PV module	12	Electrical supply
9	Solarimeter	13	Plastic bottles
10	Supplier for water		

Figure 15. Experimental setup for evaporative cooling [128]

However, even then, compared to conventional cover glass, the reduction in the temperature of the panel was only approximately 1°C [140]. A silica photonic crystal-based layer, which is a visibly transparent thermal black body, over silicon solar cells was compared to a conventional planar silica layer. The experimental study and the steady-state model indicated a decrease in temperature of approximately 1°C. The performance of the bare silicon solar cells was compared with that of an ideal thin coating of emitter, normal 5 mm thickness silica glass, and a 20-µm-thick 2D square lattice of silica pyramids (nanostructures) over a 100-µm-thick uniform silica layer. An almost ideal behavior was exhibited by the proposed layer [141].

3. Discussion

It was observed from a literature survey that various researchers have used a number of cooling methods to enhance the performance of PV panels. The relevant literature for each category is summarized in a tabular form for the reported performance parameters. The most economical and easiest way of cooling is by employing an aluminum sheet with extended surfaces on the back of the panel, which falls under the category of natural convection air cooling. Forced convection can also be employed with added advantages, but with the additional cost of infrastructure and power. The use of water would better control the temperature of the PV panel; however, this would be less attractive when there is water scarcity. Evaporation losses were typically higher when water was sprayed over the panel surface. Furthermore, the problem of scaling the surface has to be addressed, which is rarely reported. In addition, it would be futile to employ evaporative cooling during humid weather. The gain in electrical yield would be higher with the forced circulation of water compared with passive water cooling, again with an additional cost. For a dry climate, the use of absorptive materials such as cotton wicks or jute structures soaked with water would be a better alternative with comparatively less water loss. PCM cooling is another available option. The PV-thermal and PV-PCM systems were shown to have an edge over passive and active air cooling. However, the effective utilization of thermal energy for useful applications calls for a separate infrastructure or arrangement along with its own operative and maintenance costs. Attempts to increase the performance of PV-thermal and PV-PCM systems using nanofluids are quite encouraging; however, they would also require additional attention and cost to avoid the segregation of nanoparticles. Thus, although, the various methods suggested to improve the electrical yield are shown to do so, the comprehensive long term economic analysis is very rare. Each of these methods has advantages and limitations. The particular method is selected depending on the climatic conditions, availability of the cooling medium, and materials employed. Table 7 summarizes the performance comparison of different PV cooling techniques.

4. Future trends

Future advancements in cooling techniques for solar photovoltaic (PV) systems should focus on smart and adaptive cooling solutions that integrate IoT, artificial intelligence (AI), and machine learning (ML) for real-time optimization. The development of evaporative nanotechnology-based cooling materials, such as nanofluids and nano-enhanced phase change materials (PCMs), can significantly improve thermal management. Hybrid cooling approaches that combine passive and active methods, along with self-cleaning and maintenance-free solutions, enhance long-term reliability. Additionally, future research should emphasize the economic feasibility, large-scale implementation, and integration of cooling techniques with energy storage systems to maximize overall efficiency and sustainability. These innovations will drive the adoption of high-performance PV systems and support global renewable energy goals.

Table 7. Performance comparison of different PV cooling techniques.

Cooling technique	Surface temperature of PV panel reduced up to (℃)	Electrical efficiency of PV panel achieved up to (%)	Reference	Year
Air	Maximum PV surface temperature of the solar cell reduced the by 30%	Improve photovoltaic thermal efficiency by 14.019%	[142]	[2025]
Water	-	Electrical and thermal efficiencies were increased to 16.2 % and 27.2 %	[143]	[2025]
PCM with Nano and Bi fluid	-	PV panel efficiency increased by 57%	[144]	[2025]
Nano-Particle	Reduced the PV surface temperature by 19.0%	Electrical efficiency increased by 20.0%	[145]	[2022]
Evaporative	Reduction in average temperature by 18 °C	Increased in electrical efficiency by 10.13%	[146]	[2023]

5. Conclusion

The literature review presented in this paper focuses on improving photovoltaic electrical efficiency by using various cooling methods, including air cooling, water cooling, PCM cooling, the use of nanoparticles in PV-thermal and PV-PCM systems, evaporative cooling with an absorbing material structure, and radiative cooling. The findings are briefly discussed below.

- The review begins with a discussion of commercially available solar-cell materials and their conversion efficiency. The ill effect of rise in temperature on the performance of the panel is highlighted.In air cooling, changes in heat sink angles, height, thickness, width, base plate thickness, and spacing between heat sinks play an important role in lowering the temperature and improving the electrical efficiency of the PV panel.
- Forced circulation water cooling was more effective than passive water cooling.
- Photovoltaic panels attached to phase change materials and water-based systems enhance the electrical efficiency, store heat energy, and generate hot water that may be used for domestic purposes.
- The use of nanoparticles in water and PCM improves the thermal properties of these materials, which in turn improves the heat transfer rate.
- Evaporative cooling is a passive cooling method that uses a cotton wick, jute, clay, and other absorber materials along with water. This was found to effectively reduce the temperature of the PV panel.
- Radiative cooling employs a spectrally selective coating for the absorption and emission of radiation, particularly for space applications.

Conflict of interest

The authors declare that they have no conflicts of interest.

Nomenclature

Al_2O_3	Aluminium oxide
$CaCO_3$	Calcium carbonate
CFD	Computational fluid dynamics
CNs	Carbon-based nanostructures
CuO	Copper oxide
$Fe3O_4$	Ferro-magnetite
HVAC	Heating, Ventilating and Air Conditioning
KNO_3	Potassium nitrate
LPM	Litre per minute
ML	Machine learning
MPCM	Microencapsulated Phase Change Material
MWCNT	Multiwall carbon nanotube
$NaNO_3$	Sodium nitrate
PCM	Phase change material
PEG	Polyethylene Glycol
PIR	Power increment ratio
PV	Photovoltaic
PVT	Photovoltaic thermal
RO	Reverse osmasis
RT	Rubitherm
SiC	Silicon carbide
SiO_2	Silicon dioxide

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