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Review

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Cooling techniques for PV panels: A review

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Abstract: Solar energy is considered one of the most dominant renewable energy sources. It can be used to produce electricity through PV panels. Unfortunatly, this technology is subject to limitations. High operating temperature exceeding 25°C, causes the PV panels to overheat, reducing their lifetime and efficiency. Various approaches to PV cooling are used to overcome these challenges.This paper presents a comprehensive overview of different cooling techniques to increase the performance of PV panels. Passive and active PV cooling systems are analysed using air, water, phase change materials (PCMs) and nanofluids as working agents. A review analysis showed that water cooling is better than air cooling. PCMs, which have recently been gaining in popularity, also deserve attention.

Keywords: PV cooling methods, Solar energy, Photovoltaics Cooling Efficiency enhancement, Performance, PV/T

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Introduction

Fossil fuels are most polluting and dangerous energy sources, so the world is focusing its attention on modern, much safer and cleaner renewable energy sources. Next to wind energy, solar energy is currently the most widely used source of non-conventional energy. The annual amount of solar energy reaching the Earth is $1.5 \cdot 10^9$ TWh, with the world's primary energy consumption in 2021 being 176 431 TWh [1]. This means that the total energy reaching the Earth is approx. 9 500 times the level of global consumption. Solar energy from the sun in heat and light can be used for thermal applications such as thermal collectors and power purposes, as in photovoltaics. The increase in interest in photovoltaic technology in recent years is mainly due to the dropping price of photovoltaic modules. The global weighted average electricity (LCOE) cost of new commercial–scale photovoltaic projects has fallen by 13% year-on-year to 0.048 $/kWh in 2021 [2]. With the surge in interest in PV, the need for continuous improvement and development of PV technologies is increasing.

Photovoltaic cells absorb 80% of the sun's radiation, but the efficiency of converting solar energy into electricity is only 12 – 18%, with a maximum of 24% for monocrystalline cells. This means that a significant proportion of solar energy is irretrievably lost. In addition, some of the solar energy not used during photovoltaic conversion is converted to heat, leading to an increase in the temperature of the PV cells, even above 40°C relative to the ambient temperature [3]. Studies have shown that a temperature increase of about 1°C above 25°C results in a decrease in module efficiency of about 0.45%. It is vital to develop a way to prevent the cells from overheating [4,5]. In order to reduce the adverse effects associated with cell overheating, researchers are making various attempts to develop a system to increase the efficiency of photovoltaic modules.

In the context of the information presented above in this article, a comprehensive literature review has been carried out regarding photovoltaic panel cooling techniques. Active and passive cooling techniques are analysed considering air, water, nano-liquids and phase-change materials as refrigerants.

1. PV panels cooling systems

Cooling of PV panels is used to reduce the negative impact of the decrease in power output of PV panels as their operating temperature increases. Developing a suitable cooling system compensates for the decrease in power output and increases operational reliability. Different divisions of PV panel heat removal techniques can be found in the literature. Depending on the working medium, one can distinguish cooling through water, air or hybrid cooling consisting of, e.g., phase change material, heat pipes, microchannels, nanofluids or thermoelectric elements, which in various combinations yield higher or lower efficiency [6]. Regarding system structure, the modules can be classified as flat panel, concentrated, building-integrated (BIPV), and heat pump connected [7]. Modern methods of cooling PV modules are based on beam splitting (or spectral bandwidth), which distinguishes the wavelength of solar radiation reaching the cells. An of PV cooling techniques depending on the refrigerant used is shown in Fig. 1. Another well-known division concerns how the coolant is distributed regardless of its type, including active and passive cooling. This subdivision is shown in Fig. 2. The division by method of refrigerant distribution is used later in this section.

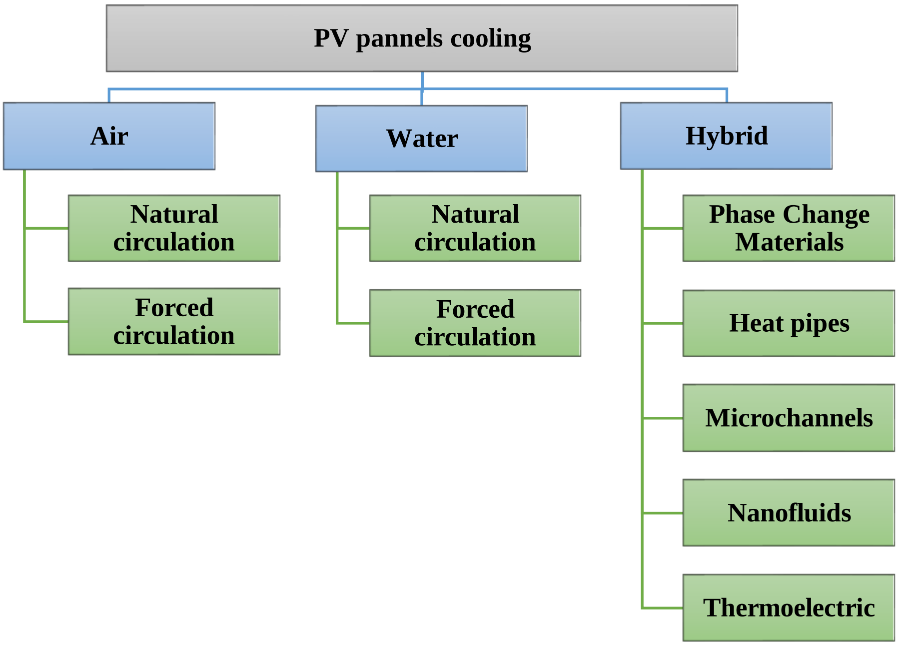

Fig. 1. Division of cooling systems based on the working fluid [8].

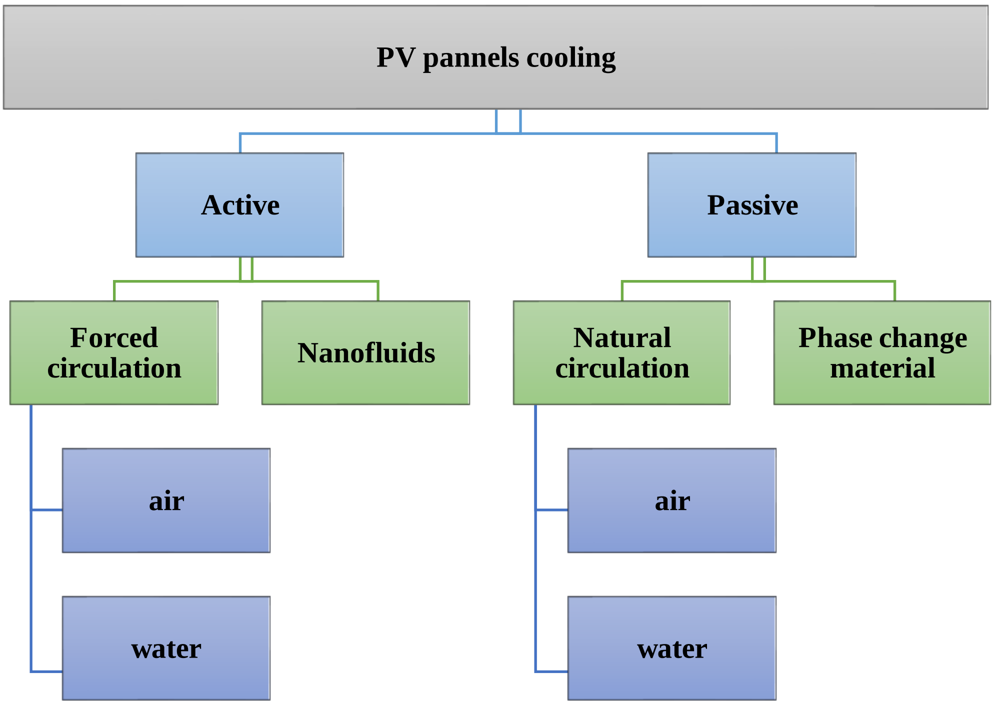

Fig. 2. Division of cooling systems by the distribution method [8].

1.1 Passive cooling

Passive cooling uses natural convection and heat conduction without mechanical components to dissipate or remove heat from photovoltaic modules. The principle of operation is based on the transport of heat from the place of generation to the environment. In order to increase the heat transfer surface of PV panels, solutions such as pipes or fins made of materials with high thermal conductivity are used. The general division of passive cooling systems consists of natural circulation cooling with air, water or phase change materials. This is the simplest way of cooling PV modules, so it is very popular. This method increases the energy efficiency and cost-effectiveness of the system with a limited investment.

1.1.1 Air cooling

Passive cooling with air is the cheapest and simplest method of removing excess heat from PV panels. In such a solution, the PV modules are cooled by natural airflow. The most common design includes fins, thin aluminium sheets or similar at the bottom of the module, which is responsible for increasing the air duct's radiative and convective heat transfer surface, causing turbulence, and acting as a heat sink. Figure 3 shows a general scheme of how air cooling works for PV panels. The literature describes several studies conducted in this field. Cuce *et al.* [9] conducted a study on the effect of passive cooling on the performance of photovoltaic cells, where an aluminium heat sink was used to dissipate excess heat. The dimensions of the heat sink were determined from previously performed steady-state heat transfer analyses. Experiments were conducted for different ambient temperature values and different solar radiation intensities. Results have shown that the proposed cooling technique increases energy conversion efficiency, exergy and cell power at the level of 20% at irradiance equal to 800 W/m^2.

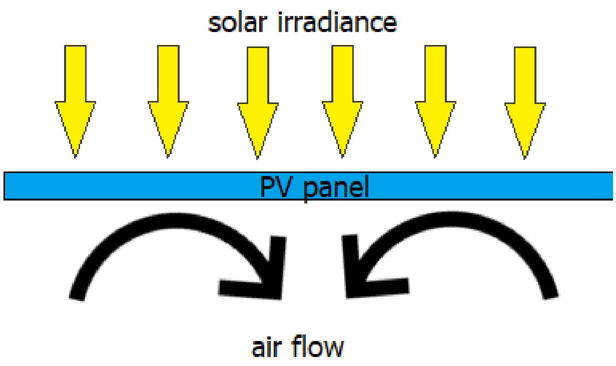

Fig. 3. Airflow cooling method.

Studies on the effect of heat sinks were also conducted by Rajput and Yang, where 197 aluminium radiation elements were mounted to the main part of the PV panel [10]. In order to ensure an adequate passive radiative cooling effect, it is required to ensure the high-temperature difference between the surroundings and the heat sink, which can be achieved by using a suitable heat transfer surface. In the present case, the authors assumed a heat sink length of 0.124 m. Tests have shown that this solution has great potential for passive heat removal from PV panels.

Passive cooling using heat sinks can also be found in Mittelman *et al.* [11]. The research used a heat sink in the form of an aluminium plate with perforated fins attached to the back of the panels. The analyses examined the effect of heat sinks on the heat transfer between the PV panel and the circulating ambient air. The heat sink was designed as an aluminium plate with perforated fins attached to the back of the PV panel. The fins of the panel were perforated to improve air circulation around them and allow more heat absorption from the PV panel. Using aluminium heat sinks could provide a potential solution to prevent PV panels from overheating and may indirectly lead to a reduction in CO_2 emissions due to the increased electricity production from the PV system. The results have shown a significant decrease in the operating temperature of the PV module and an increase in electrical efficiency. The reduction in temperature allowed the voltage and maximum operating point to increase by 10 % and 18.67%, respectively. Figure 4 shows the proposed cooling system.

Fig. 4. Cooling system using heat sinks [11].

Amber *et al.* conducted an experimental study of the performance of two passive cooling techniques [12]. The first involved using rectangular fins to dissipate excess heat from the PV modules, and the second involved using circular fins, which were placed in the back of the panels. The research was carried out over four months. The analyses showed that better efficiency could be achieved by using rectangular fins, which dissipated 155% more heat than the reference module. This solution allowed a 10.6% temperature loss of the module and a 14.5% increase in efficiency.

A completely new approach to the topic of passive air cooling was proposed by Najafi and Woodbury [13]. The authors conducted a study on PV cell cooling using the Peltier effect. In this case, a thermoelectric cooling module was attached to the back of the panels. The authors assumed that the PV panel itself would provide the energy required to run the cooling element. A detailed model of this solution was previously developed in MATLAB. The solution was investigated in two aspects. The first involved controlling the temperature of the photovoltaic cells and maintaining it at a certain level. The second aspect involved optimisation aimed at finding such a value of the current supplied to the cooling module that would lead to the maximum possible power generated by the system. The results showed that using a thermoelectric cooling module satisfied the assumed conditions.

1.1.2 Water cooling

Water is the second coolant used for PV panels excess heat removal. Liquid cooling of photovoltaic panels is a very efficient method and achieves satisfactory results. Regardless of the cooling system size or the water temperature, this method of cooling always improves the electrical efficiency of PV modules. The operating principle of this cooling type is based on water use. Water cooling includes free convection, water spray, heat pipes or immersion techniques. The flowing or sprayed water removes heat from the PV panel, lowering its temperature. A schematic water cooling system is shown in Figure 5. Collected heat from PV panels can be used in many ways. The simplest solution is to use the heated medium for domestic hot water preparation [14].

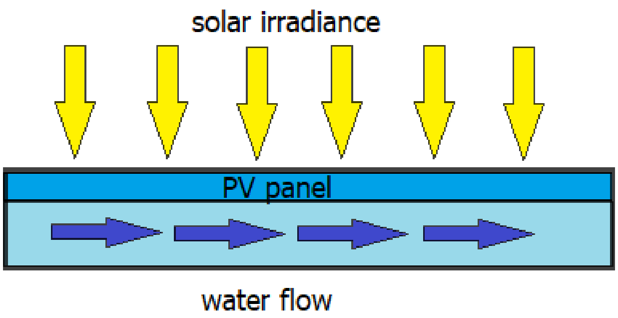

Fig. 5. water – flow cooling method.

Yang *et al.* proposed a solution where water is sprayed on the surface of the panels [15]. This system provides cooling by spraying water onto the PV panel's reverse and returning the water to the tank. The recycled water is collected in a U-shaped borehole heat exchanger (UBHE), installed in an existing well to enhance the cooling capacity. The water exchanges heat with shallow-geothermal energy. Finally, the panel is again sprayed with water to cool it. The water in this cooling system first cooled the PV panel. Then the shallow geothermal energy through the UBHE was used to cool the cooling water and maintain the cooling system's cooling capacity. Experimental results showed that the proposed solution allows a 14.3% improvement in efficiency. The solution described is shown in Figure 6.

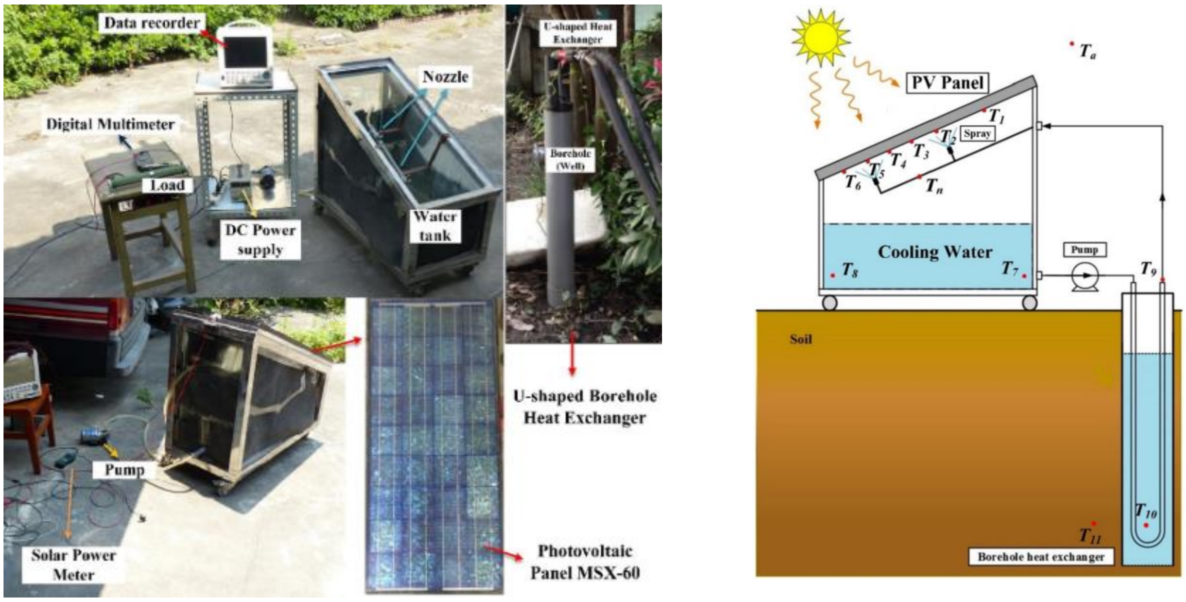

Fig. 6. Photographic and schematic view of the experimental stand.

Wu and Xiong proposed using rainwater for passive cooling, distributed through a gas expansion device [16]. The amount of water flowing through the cooling system depends on the intensity of solar radiation reaching the system. This radiation is also responsible for increasing the volume of gas in the expansion device. The proposed solution increased the electrical efficiency of the PV panels by 8.3%.

1.1.3 Phase change material cooling

Phase change materials (PCMs) are chemical compounds with a high latent heat value, ranging from 100 - 280 kJ/kg, depending on the nature of the material [17]. PCMs are characterised by their ability to retain thermal energy and allow for temperature stabilisation. These substances are readily used to remove excess heat from PV installations due to their ability to absorb and store large amounts of energy. PCMs are characterised by their ability to retain thermal energy and allow for temperature stabilisation. The phase transformation process can change the state of liquids and gases through condensation and evaporation, in turn, in the solid and liquid states through melting or freezing. As the temperature around the PCM rises to the melting point, the chemical bonds start an endothermic process that allows the PCM to absorb energy. The melting material changes its state from solid to liquid. As the temperature drops to the PCM freezing point, the bonds are regenerated, heat is released outside, and the PCM returns to its solid state. The PCM is therefore referred to as a heat reservoir. The process occurring during PCM operation and as a result of the phase, transformation results in a volume reduction of 10% from the initial volume. Commonly, PCM is applied in the back of the PV panel by applying a thin layer of PCM in an aluminium or steel-sealed housing, which is then attached to the panel. The heat extracted from the PV panel causes a phase change in the material and dissipates the heat to the outside. A general diagram of the use of PCM for cooling is shown in Figure 7. It is essential to select the PCM thermal properties so that its melting point exceeds the ambient temperature at which it will be used. If the melting point is lower than the ambient temperature, this will cause the material to liquefy before the panels heat up, resulting in the system's low performance [18].

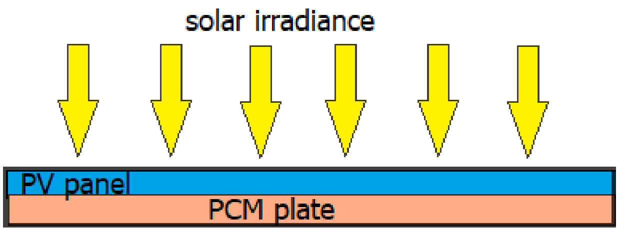

Fig. 7. PCM cooling method.

The use of phase change materials placed in the back of PV panels is described, among others, in the paper Hamdan *et al.* [19]. A PCM with a melting point close to the panels standard test condition (STC) temperature was chosen as the cooling material. A PV system consisting of two identical PV panels was studied. The PCM was integrated on the back side of one panel, while the other was kept as standard for comparison purposes. Tests carried out for 28 days showed an increase in power yield of 2.6% compared to non-cooled panels.

Arıcı *et al.* [20]presented PV cooling using paraffin wax, an organic phase change material with high latent heat. It was found that using PCM material is technically justified as it reduces the operating temperature of the PV panel by up to 10.26°C and thus increases the electrical efficiency by up to 3.73%.

The experiment reported in Waqas and Ji [21]used movable shutters filled with PCM placed at the back of PV panels. Rotatable shutters filled with PCM are attached to the back side of the panel as shown in Fig. 8. The PCM-filled shutters act as a heat sink for the PV panel during sunshine hours. Opening the shutters during non-sunny hours solved the problem of incomplete solidification of the material. The heat gained during the day was dissipated at night by rotating the louvres. The proposed system made it possible to reduce the temperature of the panels by 22°C. The maximum improvement in efficiency during the summer season was 9%.

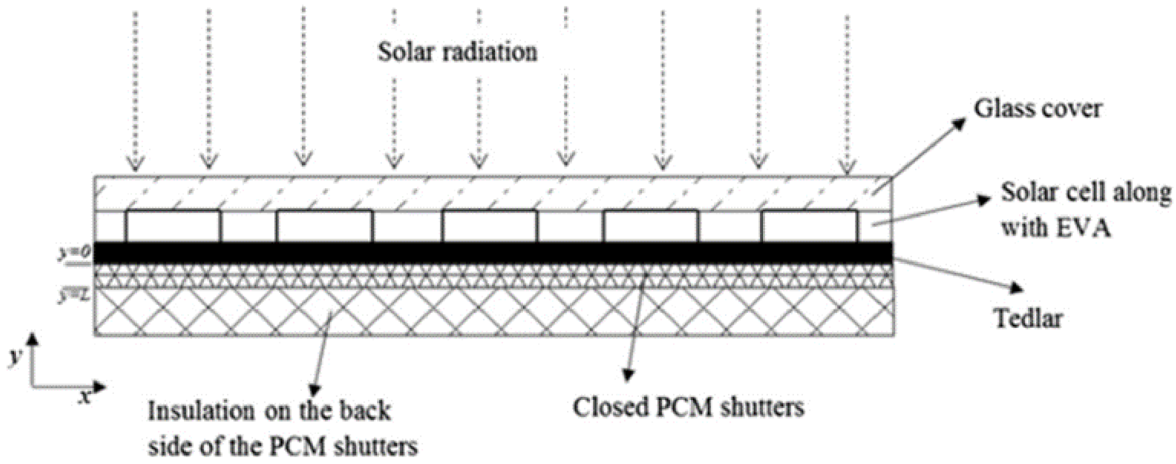

Fig. 8. Model of rotatable shutters filled with PCM [21].

Klugmann-Radziemska and Wcisło-Kucharek studied the heat flow through three phase change materials: paraffin RT-22 and rosin, characterised by different melting points. Due to the melting rate exhibited by these materials, paraffin was chosen for the final analyses. This material lowered the cell temperature by 5°C, and the effect obtained was maintained for five hours [22].

Kiwan *et al.* proposed graphite paraffin as a cooling material. A 15 mm thick layer of this chemical compound was placed under the back of the PV panels and covered with an aluminium sheet permanently fixed to the frame. The analyses confirmed the proposed solution's effectiveness, but within a certain range. It was observed that when the average temperature of the cells (around midday) exceeds the melting point of the material, the system's efficiency increases. When the temperature of the cells is lower, the PCM acts as an insulating material, which has the negative effect of blocking the possibility of easy heat dissipation [23].

Table 1. Passive cooling systems overview.

Article	Cooling system	Refrigerant	The resulting effect
[9]	Aluminium heat sink		Increase in energy conversion efficiency by 20%
[10]	Heatsink		Decrease in temperature by 23.3°C
[11]	Aluminium plate with fins	Air	Increase in voltage and maximum operating point by 10 and 18.67%.
[12]	Rectangular and circular fins		Decrease in module temperature by 10.6% and increase
[13]	Thermoelectric cooling module		Decrease in temperature by 8°C
[16]	Water spray	Water	Increase in efficiency by 14.3%.
[17]	Rainwater shower		Increase in electrical efficiency of PV panels by 8.3%.
[20]	No information available		Increase in power yield by 2.6%
[21]	Paraffin wax		Decrease in temperature to 10.26°C, increase in efficiency
[22]	Movable louvres filled with PCM	PCM	Decrease in panel temperature by 22°C
[23]	Paraffin wax, RT - 22, cereal		Decrease in cell temperature by 5°C
[24]	Graphite paraffin wax		No details available
[25]	Wax with metal shavings		Decrease in temperature by 16°C

1.2 Active cooling

The active cooling method uses a forced flow of coolant through fans, pumps or other mechanical devices to lower the temperature of PV cells. Active cooling methods primarily use forced circulations of water, air or nanofluids. It usually requires additional energy to drive auxiliary equipment but is characterised by significantly higher cooling efficiency than passive cooling. Furthermore, with active cooling methods, the waste heat from PV modules can be more beneficial [24]. Mostly active cooling systems studied in the literature are water-based and concern PVT configurations [25].

1.2.1 Air cooling

Active cooling with air has the advantage that air does not require large financial investments. Only the equipment driving the refrigerant can generate additional costs. The use of drive components also results in additional electricity consumption, which should be considered when estimating the solution's net efficiency. Active air cooling is similar to passive cooling. The only difference is that, in this case, there is forced air circulation via pumps or fans. In most solutions, cooling channels, heat sinks or fins are located at the rear of the PV panel. The following section describes some active air cooling solutions in the scientific literature.

The paper Elminshawy *et al.* [26] proposed an active solution by using pre-cooled air. A ground-air heat exchanger was used to pre-cool ambient air, which was then used as a refrigerant in the back of the PV panels. The PV cooling system was constructed by connecting a flat PV module with an active area of 1.65 m^2 with the buried EAHE. An ambient air simulator comprising a centrifugal air blower and an air heater (electric heating chamber) with controllable temperature was employed. The air heater was used to heat the induced ambient air to achieve the temperature that simulates the ambient air temperature range of arid hot climatic regions. The study showed that using such a solution at an optimum flow rate of 0.0288 m^3/s reduces the PV module temperature by about 13°C, which improves the PV module power output and electrical efficiency by 20%. Figure 9 shows the proposed cooling system.

Fig. 9. Test stand of PV panel coupled with geothermal air cooling system [26].

Tonui and Tripanagnostopoulos [27] propose another solution using air cooling. The simulations were carried out for a finned air duct mounted to the rear surface of the panels, through which the refrigerant flows. The movement of the medium was forced by using a pump. In addition, the front part of the panels was equipped with an additional glass layer. This solution resulted in a maximum thermal efficiency of 52% and an electrical efficiency of 9 - 10% under steady-state conditions.

Rahimi *et al.* [28] designed a wind device based on a conical tunnel and fabricated it to perform two functions at a laboratory scale. The first included PV cell cooling; the second was responsible for electricity production. The considered hybrid system is a combination of wind and photovoltaic systems. A vertical axis board, called a "self-steering wind vane", was installed at the top of the air tunnel to determine the wind direction. In this case, the height at which the cooling device is placed may play a significant role in easily swinging and accurately showing wind directions. As the wind hits the narrow upright tail, it spins at right angles from which the wind is blowing, so that the chamber adjusts itself in the wind stream direction. The wind flows into the inlet chamber with a wall thickness of 1 mm and rounded corners. The tests showed that the solution had great potential for further development. The total power output increased by 36% (considering both PV and turbine power). The described solution is shown in Figure 10.

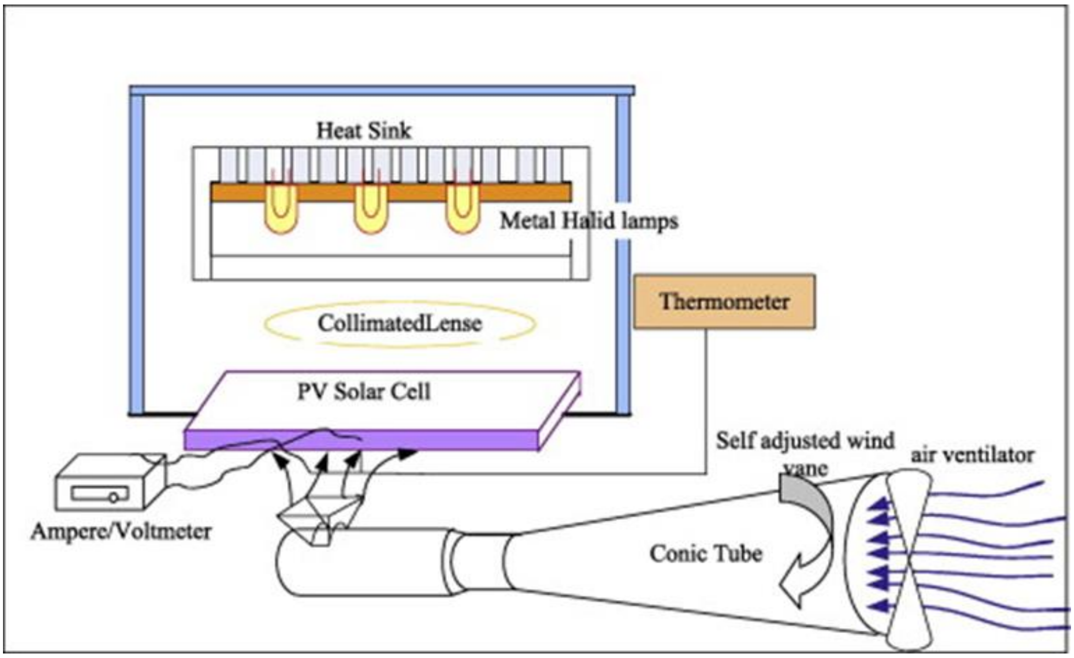

Fig. 10. Scheme of laboratory test stand [28].

Arcuri *et al*. proposed a solution involving a system of aluminium cooling channels installed at the back of the panel. The inlet and outlet openings with a square cross-section were placed on opposite sides along the long edge so that the working medium flows over the longest possible area of the PV panel. An average flow velocity of 2.3 m/s was assumed. The tested solution's average annual efficiency and electricity productions were 12.58% and 269.53 kWh, respectively [29].

1.2.2 Water cooling

Active cooling of photovoltaic panels with liquids is more efficient method than air cooling–allowing satisfactory results to be achieved. In research, water cooling is often combined with microchannels. The active water-based cooling technique uses forced water circulation through channels or tubes in the back of the PV panel.

Rahimi *et al*. studied water cooling with two microchannels: single and multi-headed. Water with different flow rates was passed through the channels. Analyses showed that multi-headed microchannels generated a greater amount of heat, decrease in average temperature and power than single-headed. The results showed a 28% increase in power and a 6.8% decrease in temperature for the multi-head microchannels [30].

Barrau *et al*. [31] investigated a solution for a device that combines the impact of a fracture jet with the uneven distribution of microchannels. In the jet impingement area, the heat flux is only absorbed by the fluid through the bottom of the heat sink. The boundary layer separation causes the increase in temperature observed. The heat exchange area, through which the liquid absorbs the heat, increases in the flow direction, adding the micro-channel surface to the surface area of the bottom of the heat sink. Within these micro-channels, the heat flux at the bottom of the heat sink gradually decreases due to the reduction of this surface and the coolant temperature increase. This is related to the heat transfer decrease throughout each micro-channel section. The net power of the proposed solution was investigated. It was shown that the minimum value of the thermal resistance coefficient was $2.18 \cdot 10^{-5}$ $(K \cdot m^2)/W$, where the previous limit reported in the literature was 10^{-4} $(K \cdot m^2)/W$. Achieving this value allowed a higher output power yield than microchannels alone. In the proposed device, it is possible to adjust the distribution of local heat dissipation capacity by modifying the internal geometry at the design stage. Figure 11 shows the cooling system model described above.

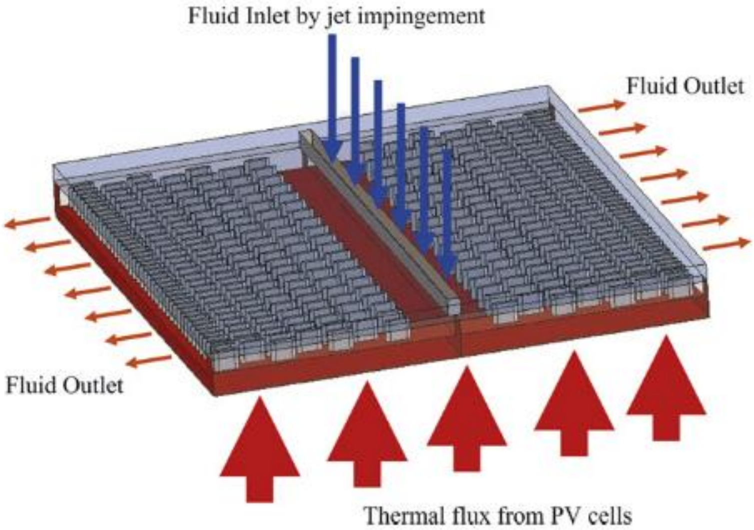

Fig. 11. Model of microchannels for cooling PV [31].

The use of a converging heat exchanger to reduce the surface temperature of the panels is presented by Baloch *et al.* [5]. The analyses compare two solutions: one with cooling and one without cooling. The study showed that the uncooled cells heated up to 71.2°C in summer, while the temperature was successfully reduced to 48.3°C when cooling was applied. This resulted in a maximum percentage increase in power output from 35.5% to 36.1%. The solution described is shown in Figure 12.

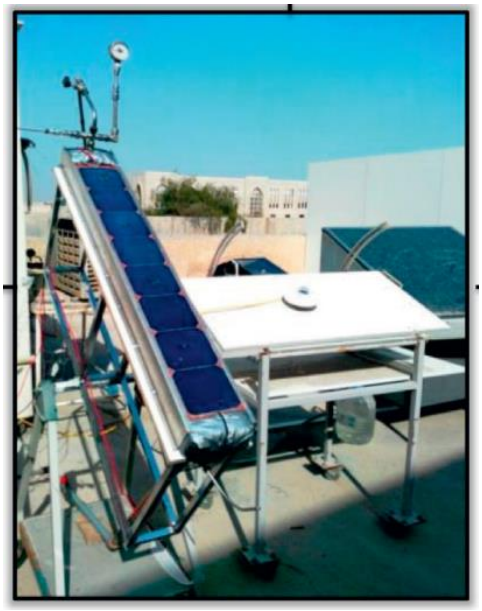

Fig. 12. Cooling system with convergent heat exchanger [5].

Water cooling of PV panels is also studied by Irwan *et al.* [32] where the performance of PV panels was compared with panels cooled by water flow on the front surface. The study was conducted under laboratory conditions. Water was sprayed on the front face of the panels. A water pump was responsible for spraying water in the cooling system. The experiment decreased panel temperature from 5 to 23°C, allowing an increase in PV panel electrical power output from 9 to 22%.

1.2.3 Nanofluid cooling

Nanofluids have high heat transfer properties due to their higher thermal conductivity compared to common liquids. These properties allow these materials to be successfully used to cool PV panels efficiently. The nanofluids efficiently remove significant waste heat, resulting in lower PV surface temperatures. It has also been shown that this type of fluid can be considered a spectral filter for PV cells because it selectively absorbs the incident infrared radiation Ali [33]. The nanofluids flow through various channels, usually microchannels, which are placed in the back of the PV panel.

The application of nanofluids for panel cooling in the form of water/(SiO_2) solution with different weight ratios in the range of 1 - 3% was proposed by Sardarabadi *et al.* [34]. The experimental setup was equipped with a storage tank, heat exchanger, circulating pump and refrigerant distribution system. The effect of nanofluids on the cooling of the PV cells at different variants of their concentration was studied. The highest decrease in operating temperature of 19°C was achieved at 3% concentration of water/(SiO_2) solution, which increased electrical efficiency from 9.2 to 11%.

Rostami *et al.* [35] presented a novel solution using atomised CuO nanofluid and high-frequency ultrasonic waves to cool PV modules. CuO nanoparticles were used for analysis due to their characteristic properties and high electrical conductivity. The nanofluids were applied through an ultrasonic atomiser, which was responsible for sending the generated cold vapour through a set of conveyor chambers to the backside of the PV panels. The atomiser power setting controlled the vapour flow rate. The results showed that using the above solution allows for an increase in cooling capacity in the range of 2.75 - 57.25% and a percentage increase in maximum power in the range of 3.4 - 51.2%, depending on the vapour flow rate or ultrasonic power.

1.3. Local climatic conditions

The cooling efficiency of PV modules depends on the chosen cooling technique and the local climatic conditions. Various environmental parameters, e.g. irradiance, ambient and module surface temperature, wind velocity, air humidity, localisation (shading, horizon line), etc. affect the performance of PV cooling. A key role among all these parameters is played by irradiance and temperature [36]. Just because a chosen cooling system performs well under given climatic conditions does not mean that it will perform with the same efficiency under other conditions. Although this issue appears relevant, a few papers in the literature compare the efficiency of PV cooling systems under different climatic conditions.

Diaz *et al.* [37] investigated the use of a PCM passive cooling system under seasonal variable atmospheric conditions in two Chilean cities (South America) with semi-arid and arid climates – Vicuña and Calama. The air temperature of the city at the semi-arid zone city varied from 10.8°C to 29.0°C, while in the city at the arid zone from 3.0°C to 24.9°C. The peak value of the inclined solar irradiation of the arid city reached 1132 W/m^2 (autumn), and during the winter, it reached 934 W/m^2. The authors presented the simplified one-dimensional PV model with an Enhanced Conduction Model. During the studies, both thicknesses of the PCM layer and the PCM type were selected. For the conditions under consideration, the best solution proved to be the use of $CaCl_2$ – 6H_2O with a thickness of 40 mm. Due to passive PV cooling, electricity generation increased by 5.8% for the semi-arid city and 4.5% for the arid city.

Table 2. Active cooling systems an overview.

Article	Cooling system	Refrigerant	The resulting effect
[26]	Ground heat exchanger		Temperature drop of 13°C
[27]	Finned duct		Thermal efficiency 52% and electrical efficiency 9 - 10%
[28]	Tapered tunnel	Air	Increase in output power 36%
[29]	Aluminum cooling channels		Average annual efficiency 12.58%,
[30]	Microchannels		Power increase 28%, temperature drop 6.8%
[31]	Microchannels		Gain in output power
[5]	Converging heat exchanger	Water	Cell temperature drop up to 48.3°C, power increase up to 36.1%
[32]	Water flow on panel		Decrease in temperature 5°C - 23°C, increase in output power 9% - 22%
[34]	Heat exchanger		Increase in electrical efficiency from 9.2 to 11%
[35]	Ultrasonic waves	Nanofluids	Increase in cooling efficiency 2.75 - 57.25%,

Dörenkämper *et al.* [38] presented experimental and simulation results in PVsyst software for a floating PV system. In this case, the electrical efficiency of the PV is enhanced by the cooling effect of the water on which the PV system floats. This is another example of a passive PV cooling technique. This paper compares the electrical performance of 46 kWp floating PV systems in the Netherlands and Singapore. The main objective of the work was to determine values of heat transfer coefficients that can be used to model the operation of systems. Also, the irradiance-weighted average temperatures of the floating PV systems have been compared with land-based reference systems. The best-performing floating PV systems showed 3.2°C (Netherlands) and 14.5°C (Singapore) lower irradiance-weighted temperatures than land- or rooftop-based reference systems. The study shows an increase in energy yield due to PV cooling use. For the Netherlands, it is 3%, and for Singapore 6%, concerning land- or rooftop-mounted PV installations.

Conclusions and future scope

This paper presents an overview of state of the art in PV panel cooling. Various aspects and approaches used to increase the performance of PV panels were analysed. Analyses have shown that both active and passive cooling methods contribute to reducing the rate of panel temperature rise over time and maintaining panel temperatures within the nominal operating range specified by the manufacturer. Active cooling techniques are an effective way to improve photovoltaic performance but depend on an external power source. This causes the external power (source) to be subtracted from the power generated by the photovoltaic cells, reducing the net output power generated from the photovoltaic cells. Active cooling is an efficient technique, despite the higher financial outlay associated with the investment and subsequent maintenance costs. Active cooling systems can be efficient if the heat energy gained is put to practical use, e.g. in domestic or commercial applications. Passive cooling techniques are simple, straightforward and inexpensive, but are characterised by a low heat transfer rate, so they do not allow for a significant increase in photovoltaic efficiency. PCM cooling is considered one of the promising methods for photovoltaic cooling, but due to the low thermal conductivity of PCM, it requires further research. The thermal conductivity of PCM can be improved by adding another component which will benefit the cooling performance. An example of this could be the combination of PCM, nanoparticles and microchannels/heat pipes, which can significantly increase heat transfer and electrical efficiency.

Research into new cooling solutions for PV panels is constantly being carried out around the world, and an efficient cooling system is anticipated to be developed soon. In our opinion, several aspects would require more attention. These include:

1. There should be research into practical and efficient solutions that could be applied to commercial solutions.
2. There is a need to develop research into concentrated photovoltaics that can generate more power than current technologies.
3. It is worthwhile to carry out additional technical and economic analyses to reduce payback time and financial outlay using a rational cooling approach.
4. Research into potentially unprofitable solutions with no prospects should be avoided.
5. In the case of research into active cooling methods using water/nanofluids and PCMs, the operational reliability of such solutions should be taken into account, and efforts should be made to reduce the operating costs of such systems.
6. In PCM-based cooling methods, materials must be selected so that melting and solidification occur spontaneously. Additional subcooling may contribute to insufficient solidification of the PCM, resulting in a loss of performance.
7. Where possible, research into cooling methods should be carried out in different climatic zones to assess effectiveness under different operating conditions.

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