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Enhancing Photovoltaic Performance through Water-Based Cooling: A Comprehensive Review of Passive and Active Techniques

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Abstract

The use of renewable energy is being advanced in large part by photovoltaic (PV) panels. Their effectiveness is severely reduced by high working temperatures, though, underscoring the necessity for efficient cooling systems to improve performance and sustainability. Photovoltaic panels have a decline in efficiency when operating temperatures increase, with crystalline silicon cells exhibiting a 0.45–0.6% reduction in efficiency for each degree Celsius rise. This study offers a comprehensive assessment of water-based cooling strategies, recognised as highly effective methods for improving photovoltaic performance and sustainability. Methods are categorised as passive systems (immersion, floating photovoltaic, evaporative cooling) and active systems (water spraying, photovoltaic/thermal collectors, micro-channels, jet impingement, geothermal exchangers). Reported findings indicate that water-based cooling can reduce PV module temperatures by up to 46%, enhance electrical efficiency by 6–38%, and increase power output by as much as 47%, depending upon the design. Active systems provide superior cooling but elevate operational expenses; passive systems are more straightforward and energy efficient. This paper presents the inaugural comprehensive review exclusively addressing water-based photovoltaic cooling, supplemented with a section on hybrid water cooling systems that integrates technical performance with a succinct assessment of the economic and environmental impacts. The manuscript delineates critical research deficiencies, such as long-term reliability and urban integration, while providing strategic recommendations for the advancement of more sustainable photovoltaic systems.

Keywords: Photovoltaic Cooling; Water-Based Cooling Systems; Passive and Active Cooling; Thermal Management; PV Efficiency Enhancement; Renewable Energy Sustainability.

Highlights:

1. PV efficiency drops 0.45–0.6% per °C rise in operating temperature.
2. Water cooling lowers PV module temps by up to 46%.
3. Electrical efficiency improves by 6–38% with water cooling.
4. Power output increases up to 47% using water-based cooling.
5. First review dedicated to water-based PV cooling systems.

Nomenclature:

PV: Photovoltaic
CdTe: Cadmium telluride
CIGS: Copper indium gallium selenium
FPV: Floating photovoltaic
SPV: Spray nozzle photovoltaic
EWHE: Earth water heat exchanger photovoltaic
LPV: Land based photovoltaic
EC: Evaporative cooling photovoltaic
PVT: Thermal photovoltaic
PCM: Phase change materials
PVPS: Photovoltaic water pumping system
JIC: Jet impingement cooling
MCPH: Micro cooling heat pipe
CIS: Cooling in summer
HIW: Heating in winter
MWCNT: Multi-walled carbon nanotube
IoT: Internet of Things
AI: Artificial Intelligence
Al₂O₃: Aluminium Oxide
ZnO: Zinc Oxide
CuO: Copper (II) Oxide

1. Introduction

The ongoing increase in energy consumption, fuelled by rapid developments in technology in sectors such as healthcare, transportation, and communication, has positioned energy system optimization and the development of sustainable management strategies as urgent and critical research areas [1-2]. The need to manage increasing energy demands with key concepts of efficiency, sustainability, and reliability is central to this dilemma [3-4].

Ongoing efforts are increasingly focused on improving energy distribution networks, simplifying consumption patterns, and developing technologies that not only meet societal

needs but also considerably minimize environmental effect [5-6]. These policies seek to create a smarter, cleaner, and more resilient energy future that balances economic growth with environmental responsibility.

Energy generation is a critical cornerstone for every nation's development and economic growth. A reliable and sustainable energy supply drives industrial progress, technological advancements, and overall societal well-being. However, energy production from conventional sources such as coal, fossil fuels, and geothermal plants can have significant environmental consequences if not managed responsibly. These methods often release pollutants, contributing to ecological degradation, climate change, adverse health impacts, and trap solar heat, resulting in the warming of the planet [7]. Striking a balance between energy needs and environmental stewardship is essential to ensure long-term sustainability and global ecological harmony [8].

Today, solar energy is regarded as one of the most vital and abundant renewable energy resources, primarily harnessed through PV panels. Unlike fossil fuels, solar energy produces no greenhouse gas emissions, making it a far more sustainable option. Solar energy has a wide array of applications globally, including electricity generation, water heating, and powering off-grid locations. They are also used in telecommunications, public lighting, agriculture, water heating and pumping, water desalination, satellites, space vehicles, etc. [9]. The adoption of solar energy not only promotes sustainable development but also reduces our reliance on fossil fuels and significantly lowers carbon dioxide emissions.

Solar energy, generated from solar radiation through the photoelectric effect, is harnessed using various technologies, primarily photovoltaic panels. These panels convert sunlight into electricity via semiconductor materials. The use of this technology offers significant environmental benefits by reducing carbon dioxide emissions. Additionally, it provides economic advantages by lowering electricity bills and reducing operational costs.

However, as the temperature of a photovoltaic panel increases, its thermal and electrical efficiency decreases, leading to a reduction in power output. Studies have shown that for crystalline silicon solar cells, there is a 0.45–0.6% decrease in efficiency for each degree Celsius increase in temperature [10].

To address this issue, researchers are actively developing methods to cool photovoltaic cells and enhance their efficiency. Various cooling techniques, utilizing either natural (passive) or forced (active) convection, are being investigated. Passive cooling, such as hybrid PVT systems, relies on natural convection and does not require additional electric power; the excess heat is dissipated naturally. In contrast, active cooling methods use electric power, such as pumps and fans, to cool the PV cells. While this approach is more effective and efficient at heat removal, it incurs additional energy costs. Figure 1 shows the most used types of cooling methods: active and passive.

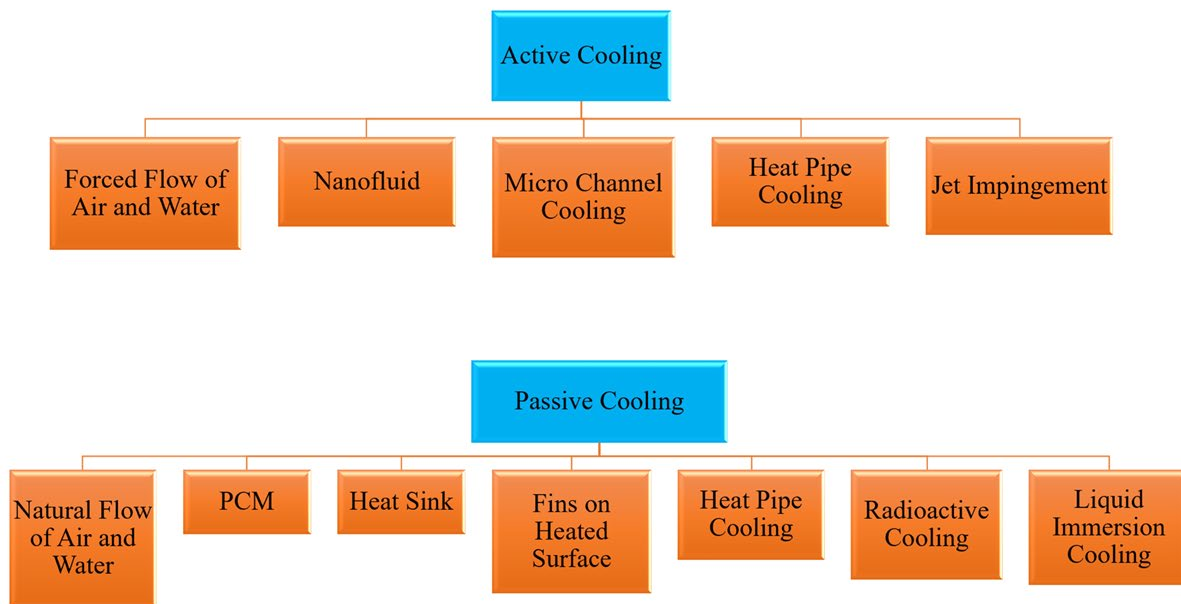


Fig. 1. Active and passive PV cooling techniques.

Given the growing interest in solar cooling methods, a substantial number of studies have been conducted in this area. Looking ahead, comprehensive review papers that highlight the latest advancements in cooling techniques will be crucial for the continued development of this field. Some of the recent studies conducted by researchers on the concept of cooling techniques, such as El Kassar et al. [11] provide a comprehensive overview of current research, offering a detailed categorization and critical analysis of four different PCM-based cooling methods, findings show that pure PCMs like hydrated salt HS36 and paraffin RT42 significantly improve electrical efficiency, with further gains from composite PCMs containing carbon-based additives and magnesium oxide. Finned PCMs with zinc nanoparticles and aluminum fins also enhance performance. Additionally, hybrid PCM systems, such as PVT-RT35HC with graphene nanofluids, provide notable efficiency and power improvements, reflecting a recent trend toward hybrid PCM-based cooling solutions. Gao et. al [12] examines the integration of

various heat pipes with solar PV systems, incorporating insights from both recent advancements and historical developments in cutting-edge technology, Saxena et al. [13] examines the efficacy of sustaining low photovoltaic temperatures using front-surface water cooling and back-surface cooling utilising a phase change material-based heat sink in three distinct configurations within the climatic context of Moradabad, India. The identical reference module was compared with (i) a front-surface water-cooled system; (ii) a back-surface PCM-cooled module; and (iii) a system that was water-cooled and PCM-cooled in a time-dependent manner. The average surface temperature decreased by 78.7% in the first configuration, 25.7% in the second configuration, and 36.8% in the third configuration. The net average enhancement in electrical conversion efficiency was approximately 22.8%, 7.8%, and 10.3% for the first, second, and third configurations, respectively.

Moreover, the review done by Elavarasan et al. [14] encompasses strategies grounded in convective and radiative heat transfer principles, utilizing heat pipes, air, water, phase change materials, and nanofluids (suspensions of nanoparticles) as heat-exchange media. It includes detailed descriptions of their unique properties, advantages, limitations, and potential applications. Table 1 provides an overview of various review papers conducted by researchers on cooling techniques for photovoltaic (PV) panels. These studies highlight a diverse range of cooling methods aimed at reducing the operating temperature of solar panels, thereby improving their efficiency.

Table 1: Summary of review papers on some cooling methods of photovoltaic panels.

Authors	Cooling Method
Al Kassar et al. [11]	PCM-based cooling system
Gao et al. [12]	Heat pipe photovoltaic cooling
Saxena et al. [13]	Phase change material and Heat sink
Elavarasan et al. [14]	Proposed a wide range of cooling methods
Suresh et al. [15]	Cooling using nanofluids
Othman et al. [16]	Air cooling method
Bilen et al. [17]	Different cooling strategies
Aarti et al. [18]	Thermoelectric cooling

Based on the facts and based on the literature review performed, the below research gaps have been identified:

1. **Limited Comparative Analyses:** Although several cooling strategies for photovoltaic (PV) panels have been investigated, thorough comparative studies assessing the efficacy

of various water-based cooling techniques specifically, differentiating between passive and active systems are scarce.

2. **Integration with Built Environments:** Few research has looked at how water-based cooling systems can be successfully incorporated into current urban infrastructures and architectural designs to improve the performance of PV panels in the built environment.
3. **Long-Term Performance Information:** There aren't many long-term studies that evaluate the longevity, upkeep needs, and performance deterioration of water-based cooling systems over time.

Although numerous publications have examined various cooling procedures for solar systems, the majority offer just basic summaries or concentrate on technologies without differentiating between passive and active water-based techniques. Furthermore, most current research focusses solely on technical performance, neglecting economic viability, environmental consequences, and practical implementation in real-world scenarios. This study provides the inaugural complete assessment solely focused on water-based cooling systems, rigorously contrasting passive and active techniques. This study integrates technological, economic, and environmental views to establish a comprehensive framework that surpasses previous endeavours, identifies significant research gaps, and provides essential recommendations for academics and practitioners.

The review starts by outlining the main factors affecting solar cell efficiency and providing an explanation of the photoelectric effect in photovoltaic cells, including basic electrical equations. After that, it provides an overview of the most recent developments in PV panel cooling systems, classifying and evaluating several water-based cooling strategies using easy-to-understand visual schematics. The study fills in current research gaps by combining new advancements, especially the requirement for methodical comparisons and assessments of water-cooling techniques with respect to their technical, financial, and environmental benefits. Key points of originality of the work are as follows:

1. **Focused Analysis of Water-Based Cooling Techniques:** This review covers water-based cooling techniques in a novel way, offering a thorough comparison of passive and active systems that is not as well-covered in the literature.
2. **Strategic Insights for Implementation:** The review offers useful insights into how water-based cooling systems can be successfully used in real-world situations by going over how they are integrated into the built environment.

3. **Visual Representation:** Including thorough schematics and visual aids improves comprehension and makes comparing various cooling methods easier, which makes the material more understandable and accessible.

By bridging the gap between theoretical models and real-world applications, this thorough assessment is an invaluable tool for engineers and academics working to develop more sustainable and efficient photovoltaic systems.

2. PV Panels and theoretical background

2.1. *Theoretical Framework for Photovoltaic Cooling Technologies*

The efficiency of photovoltaic (PV) panels is significantly affected by operation temperature; increased cell temperatures lead to semiconductor band gap narrowing, which raises carrier recombination rates and diminishes open-circuit voltage. Empirical studies demonstrate that electrical efficiency generally diminishes by 0.4–0.5% for every 1 °C increase over the normal test condition of 25 °C. The thermal sensitivity has prompted the creation of theoretical models for photovoltaic thermal management, integrating energy balance equations with heat transfer mechanisms to forecast panel temperature and efficiency under diverse environmental conditions. These models typically incorporate radiative, convective, and conductive heat transfers, in addition to absorbed solar irradiance and electrical conversion inefficiencies. Advanced frameworks blend computational fluid dynamics (CFD) and finite element approaches to evaluate the effects of cooling solutions, facilitating system design optimisation by assessing aspects such as coolant flow rate, material characteristics, and shape. These theoretical frameworks offer critical insights for the design of efficient thermal management systems intended to reduce temperature-related efficiency losses in photovoltaic panels.

2.2. *The Physics of the Photovoltaic Cell*

The photovoltaic effect occurs when photons are absorbed by a semiconductor, exciting electrons and generating an electric current. In silicon-based PV cells, electrons bound in the

crystal lattice gain mobility upon absorbing light energy, a principle first observed by Becquerel in 1839 and advanced with the modern silicon solar cell by Ohl in 1946 [19]. The built-in electric field at the PN junction drives electrons toward the N-region and holes toward the P-region, creating a potential difference that produces direct current (DC) when a load is connected as shown in Fig. 2. Structurally, a PV cell consists of a thin N-layer and a thicker P-layer to optimize light absorption, along with conductive fingers and busbars that collect, and transport electrons see Fig. 3b. Individual cells are connected in series and parallel to form solar arrays as shown in Fig.3a, which combine to generate usable electrical power.

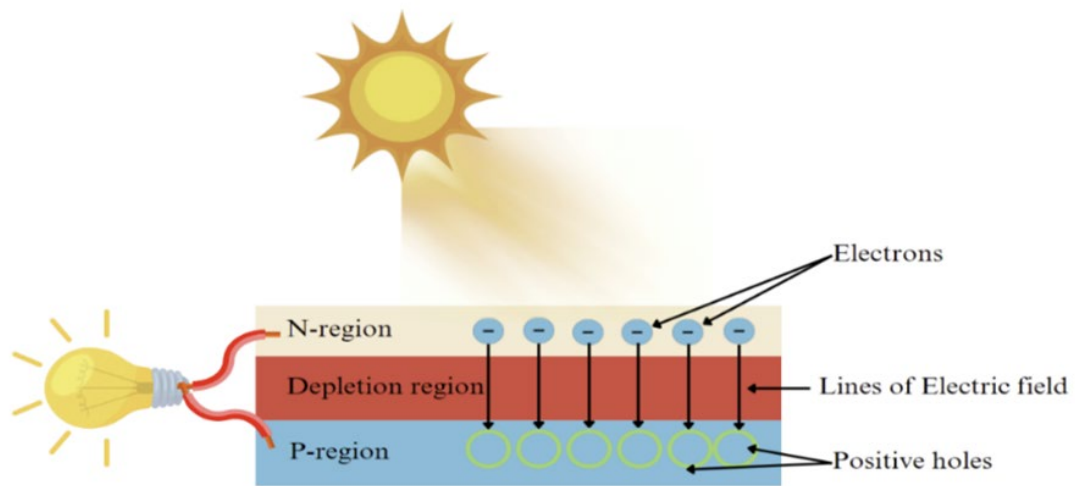
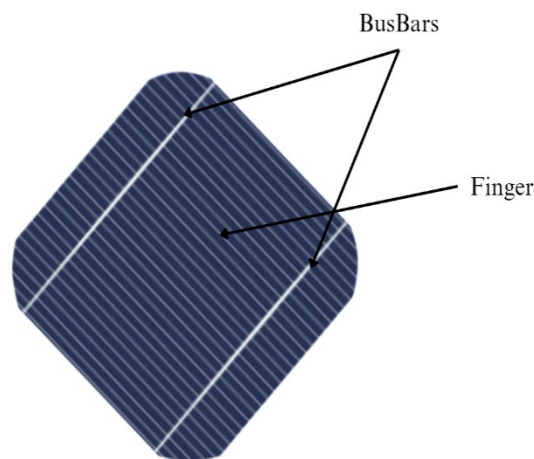
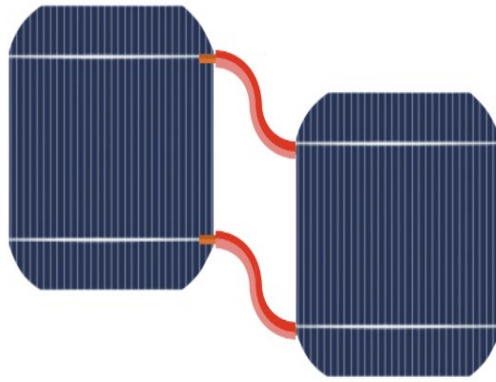


Fig. 2. Semiconducting materials of a PV cell, the electrons, and the positive holes.



(a)



(b)

Fig. 3. The fingers and the busbar of a solar cell and (b) Connection of solar cells in series to form a string.

2.3. The Generations of PV Cells

Photovoltaic panels are categorized into four generations based on the technologies used in their production. The first generation comprises silicon-based panels, while the second generation includes thin film cells. These technologies are prevalent in commercial PV panels. In contrast, the third and fourth generations, which involve emerging technologies, are still largely experimental [21-22]. Crystalline silicon panels dominate the market due to their high photoelectric conversion efficiency, cost-effectiveness in manufacturing, and exceptional durability. Currently, crystalline silicon panels hold a commanding 92% share of the global photovoltaic market. Other types of panels include cadmium telluride (CdTe), which represents approximately 5% of the market, and copper indium gallium selenium (CIGS), which accounts for about 2% [23-24-25]. Table 2 summarizes the different generations of the PV panels.

Table 2: Photovoltaic panels and solar type [26].

Generation of PV	Type
1st generation	a) Monocrystalline
	b) Polycrystalline
2nd generation	a) Cadmium telluride (CdTe)
	b) Amorphous silicon (a-Si)
	c) Copper indium gallium selenide (CIGS)
3rd generation	a) Dye-sensitized solar cell (DSSC)
	b) Quantum dots (QD) solar cell
	c) Perovskite solar cell
	d) Organic solar cell
4th generation	a) Metal Oxides/ nanoparticles

2.4. Governing equations

To calculate the area of a photovoltaic panel, you will typically need to know the panel's dimensions (length and width). The area of the PV panel can be calculated by the following equation [27]:

$$A = L \times W \quad (1)$$

A: the total area of the PV panel (m^2)

L: Length of the PV panel (m)

W: width of the PV Panel (m)

Not all the surface area of a photovoltaic (PV) panel contributes to radiation absorption. Instead, the effective area, which directly impacts the amount of power received must be calculated. The effective area is determined by multiplying the area of a single cell within the panel by the total number of cells in the panel. This calculation is represented by Equation (2) below [27]:

$$A_{eff} = A_{cell} \times Nb_{cells} \quad (2)$$

A_{eff} : The effective area of the PV panel (m^2)

A_{cell} : Area of one cell (m^2)

Nb_{cells} : number of cells forming the PV panel.

The input power received by a solar cell is primarily determined by the solar irradiance, which represents the power per unit area that the solar panel absorbs from sunlight. This power is in the form of electromagnetic radiation, specifically light, which is captured by the solar cells and subsequently converted into electrical power. The magnitude of the input power is influenced by several factors, including solar radiation, the glass absorptivity and transmissivity, and the effective area of the solar panel. Equation (3) illustrates how to calculate this input power [27]:

$$P_{input} = P_{solar} = G \cdot \alpha \cdot \tau \cdot A_{eff} \quad (3)$$

P_{Input} : The input solar power (W)

G: Solar radiation intensity incident on the panel (W/m^2)

α : Glass absorptivity.

τ : Glass transmissivity.

The output power of a solar panel is the electrical power generated after it converts the absorbed solar irradiance (input power) into usable electricity. This output power is determined by the voltage and current produced by the panel. The relationship between these factors is captured in Equation (4), which demonstrates how to calculate the output power of the solar panel [27]:

$$P_{output} = P_{electric} = V_{out} \cdot I_{out} \quad (4)$$

P_{output} : The electric output power (W)

V_{out} : The voltage produced by the PV panel (V)

I_{out} : The intensity of the electric current generated by the PV panel (A)

Each solar panel is characterized by its efficiency, which indicates how effectively the panel converts absorbed solar energy into electrical power. Higher efficiency means better performance, as the panel converts more sunlight into electricity. To calculate the electrical efficiency, we divide the output power by the input power. This relationship is expressed in Equation (5) [27]:

$$\eta_{electric} = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{electric}}{P_{solar}} \times 100 \quad (5)$$

The thermal efficiency of a solar panel refers to the panel's ability to convert absorbed sunlight into heat, which is then transferred to the fluid circulating within the system. While solar panels are primarily designed to convert solar irradiance into electrical energy, they also absorb a portion of the sunlight as heat. This heat is often lost to the surroundings, but understanding the thermal efficiency helps quantify how much of the absorbed energy is retained as heat versus how much is converted into useful electrical power. The thermal efficiency can be calculated using Equation (6) [28]:

$$\eta_{thermal} = \frac{\dot{m}C_p(T_{water-out} - T_{water-in})}{P_{solar}} \times 100 \quad (6)$$

\dot{m} : mass flow rate ($\frac{Kg}{s}$) C_p : heat capacity at constant pressure ($\frac{J}{Kg.K}$)

$T_{water-out}$: Temperature of the outlet water (K) $T_{water-in}$: Temperature of the inlet water (K)

As previously mentioned, a photovoltaic (PV) panel converts absorbed solar energy into both electricity and heat. By considering the efficiencies of both processes, as outlined in equations (5) and (6), we can determine the total efficiency of the solar panel. This total efficiency represents the combined effectiveness of the panel in converting solar irradiance into usable electrical power and heat energy, as shown in equation (7) [28]:

$$\eta_{total} = \eta_{electric} + \eta_{thermal} \quad (7)$$

2.5. *Environmental factors affecting the efficiency of the solar panel*

The efficiency and output power of photovoltaic (PV) panels are influenced by a variety of factors, including the type of PV technology, environmental conditions, system technology, and the overall quality of grid-connected PV systems [29]. Through both mathematical models and field tests, researchers have identified several factors beyond panel temperature that affect efficiency. Jathar et al. [30] reviewed these environmental variables, providing a comprehensive analysis as illustrated in Figure (4).

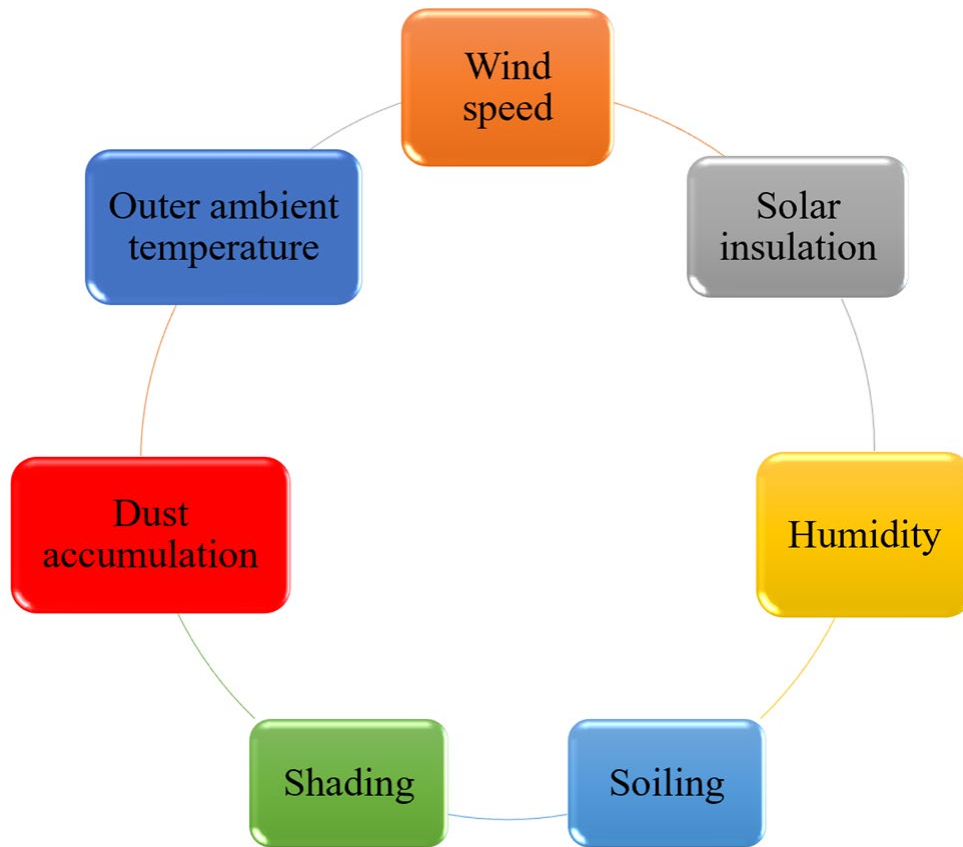


Fig 4. Shows the environmental parameters affecting the efficiency of a PV module [30].

2.6. The temperature and the efficiency of PV cell

Temperature plays a critical role in the efficiency degradation of photovoltaic (PV) panels due to the inherent properties of photovoltaic materials, which convert sunlight into electricity [29]. PV cells generate electricity from sunlight primarily within the wavelength range of 700 to 1100 nm. Wavelengths outside this range are either reflected or pass through the panel, leading to increased heating and elevating the panel's temperature above its optimal operating range [31]. For different types of photovoltaic panels, a temperature increase of 1°C above the standard 25°C can result in a decrease in efficiency by approximately 0.5-0.6% [32-33-34]. Consequently, researchers are actively seeking effective cooling methods to mitigate temperature rise and enhance both electrical and thermal efficiencies. The following equation illustrates the relationship between temperature and PV panel efficiency. Here, a and b are constants specific to the type of photovoltaic panel [35]:

$$\eta = a - b(T_{panel} - T_{amb}) \quad (8)$$

This equation demonstrates how the efficiency of the PV panel declines as the temperature difference between the panel and the ambient environment increases.

3. Cooling Techniques

Photovoltaic panels are rapidly becoming a crucial component of sustainable energy generation, driven by the global demand for renewable energy sources. However, elevated temperatures can significantly impair the efficiency of solar panels, leading to reduced power output. To address this challenge, various cooling techniques have been developed, aiming to enhance efficiency and extend the lifespan of photovoltaic systems. Figure 5 shows the main cooling techniques discovered by researchers all over the world, classifying them into four categories.

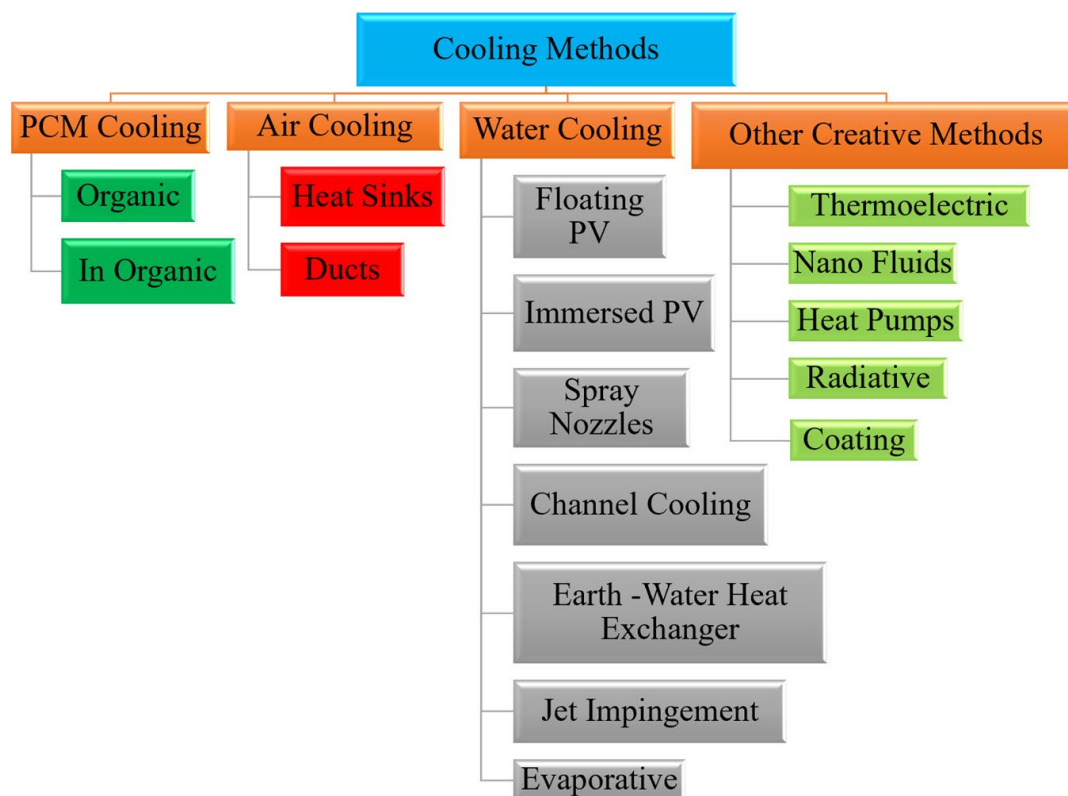


Fig. 5. Different cooling techniques and their classifications.

3.1. Phase Change Materials based Cooling

Phase change materials (PCMs) are substances that absorb and release thermal energy during phase transitions at specific temperatures. Based on their chemical composition, PCMs can be classified into three categories: organic, inorganic, and eutectic materials. Inorganic PCMs include salt hydrates, salts, metals, and alloys, while organic PCMs consist of paraffins, non-

paraffins, and polyalcohol's [36]. Eutectics are a combination of two or more components that solidify or melt simultaneously at a particular ratio.

PCMs are also categorized by their phase change states into solid-solid, solid-liquid, and liquid-gas groups. Among these, solid-liquid PCMs are particularly suitable for thermal energy storage and management in various applications due to their high latent heat, ability to maintain a constant temperature during phase transition, and stability over many cycles.

Phase change materials (PCMs) can store 5 to 14 times more heat compared to sensible heat storage materials at a constant temperature [37]. To be effective for thermal storage, PCMs must possess several key properties: a high latent heat of fusion, high specific heat, and high thermal conductivity. Additionally, they should exhibit minimal volume change during phase transition and have little or no sub-cooling.

For practical applications, PCMs need to be chemically stable over numerous thermal cycles and should be non-toxic, non-corrosive, and non-flammable. Furthermore, they should be available in large quantities at an affordable price to ensure widespread usability [38]. These characteristics are essential for the reliable and efficient performance of PCMs in various thermal management systems.

Integrating specific phase change materials (PCMs) with photovoltaic (PV) panels creates a hybrid system that passively reduces the surface temperature of PV cells, thereby enhancing their electrical conversion efficiency. In this hybrid setup, the PCM functions similarly to a heat sink, absorbing excess heat from the PV cells and lowering their temperature. This passive cooling effect can reduce the temperature of PV panels by more than 10°C and improve electrical efficiency by over 5% [29]. However, the effectiveness of this cooling strategy is contingent upon the properties of the PCM and the surrounding environmental conditions.

Mousavi Baygi et al. [39] investigated the use of polyethylene glycol as a phase change material (PCM) for cooling photovoltaic (PV) panels. Their findings demonstrated that incorporating polyethylene glycol led to an increase in the electrical efficiency of the PV panel by up to 8%. Similarly, Müslüm Arıcı et al. [40] reported that using organic PCMs with various melting points resulted in an improvement in electrical efficiency of up to 3.73%. Farouk Hachem et al. [41] explored both pure and combined PCMs for cooling PV panels, observing an average increase in electrical efficiency of 3% with pure PCMs and 5.8% with combined PCMs.

Figure 8 illustrates the experimental cooling setup for a photovoltaic (PV) panel, as conducted by Hasan Ahmad et al. [42], using an integrated phase change material (PCM) container as shown in Fig. 6. The container was fabricated from 4 mm thick aluminum alloy (1050A) and designed with straight vertical back-to-back fins spaced 7 cm apart horizontally to enhance

thermal performance. The PCM used was commercial RT42, which was melted at 80°C, filled into the container, and allowed to solidify at 25°C. A 7 cm free space was left at the top of the container to accommodate volume expansion and release trapped air during successive melting and solidification cycles. The container was securely bonded to the PV panel with epoxy resin under pressure to ensure structural integrity.

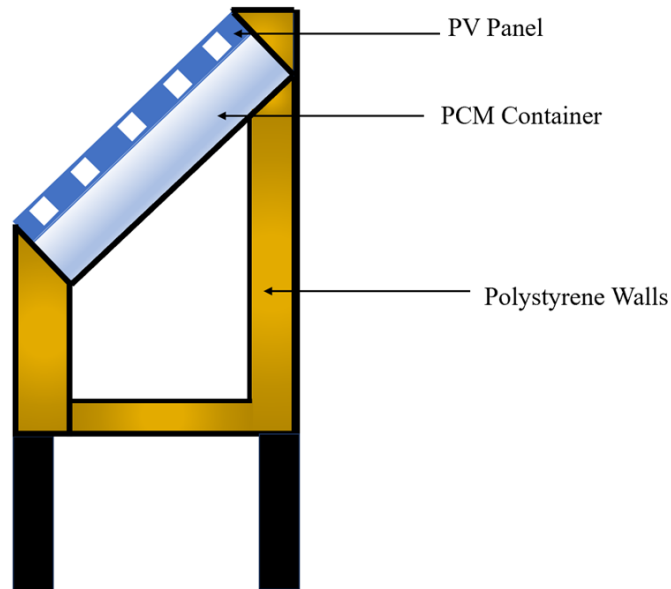


Fig. 6. PV panel integrated with PCM cooling [42].

Current research focuses on innovative PCM cooling techniques that integrate PCMs with additional cooling methods to achieve even better performance outcomes.

3.2. Air based Cooling

One of the most important methods for improving the effectiveness and performance of solar energy systems is air cooling of photovoltaic. PV panels absorb heat from the sun and produce power, which can result in higher temperatures and decreased efficiency. By helping to disperse this extra heat, air cooling, either passive or active, maintains the PV cells' ideal operating conditions. This method efficiently reduces the panels' surface temperature, boosts their electrical production, and lengthens their lifespan by using forced or natural air circulation. Air cooling is a straightforward yet powerful tactic to increase the longevity and efficiency of photovoltaic installations in the context of sustainable energy solutions.

Recent studies show that cooling the photovoltaic panel through air could be done by several creative and innovative methods. Some researchers modify the design of the panel, for example, by creating air holes inside the PV panel as shown in Fig 7.

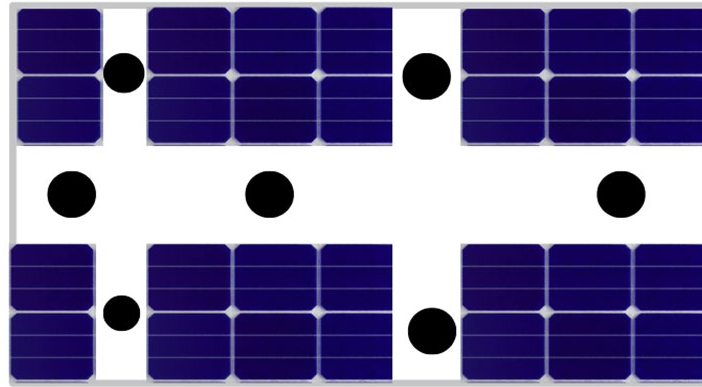


Fig.7. PV panel with air holes [43].

Others work on integrating heat sinks of different designs, dimensions, and material selection along with the photovoltaic panel to enhance natural convection for example as the one illustrated in Fig 8.

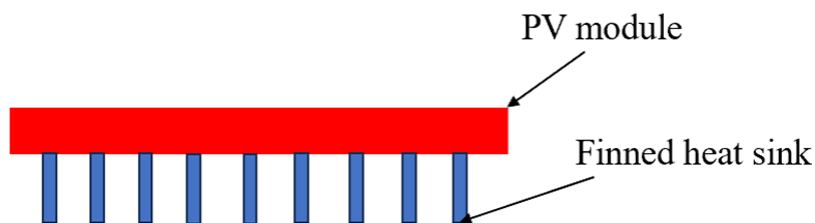


Fig. 8. PV module with finned heat sink [44].

PV panel temperatures can be lowered by up to 6 °C with a well-designed heat sink, boosting electrical performance by more than 4% [29].

Hernandez-Perez et al. [45] use a new passive heat sink design. The results show a 4% increase in electrical efficiency, achieving a temperature reduction of around 10 °C. Hussain et al. [46] uses a honeycomb heat exchanger, as shown in Fig 9.

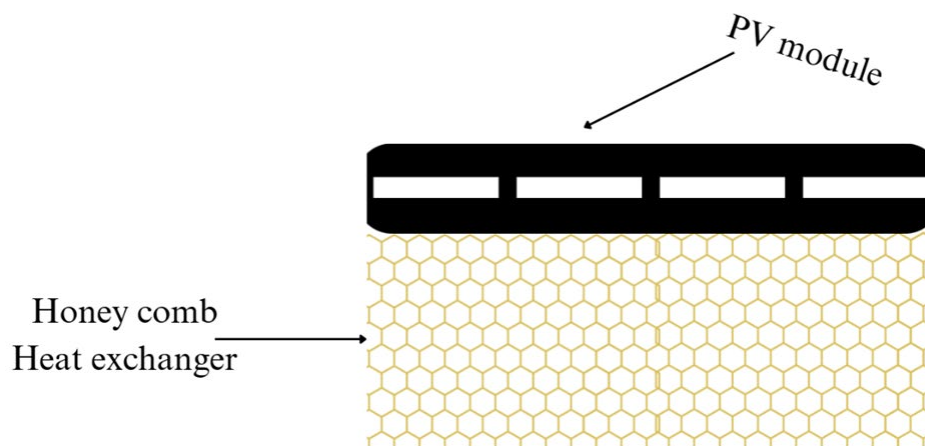


Fig. 9. PV panel with honeycomb heat exchanger [46].

The experiment shows that the electrical efficiency of the module increased by 0.1%, while the thermal efficiency increased from 27 to 87%.

The efficiency of an underground heat exchanger system for cooling solar panels in hot weather was investigated by Nabil A.S. Elminshawy et al. [47]. It was shown that when ambient air was supplied to (BHE) at 35 °C, 40 °C, and 45 °C, respectively, geothermal air cooling increased average daily power efficiency by 29.11 %, 23.61%, and 18.46%.

In addition, scientists cooled the Photovoltaic panel using different air collectors. Studies show that the higher the airflow rate, the lower the PV temperature. This cooling method can cause the efficiency to improve by 3.5 to 6%.

Moreover, researchers use the geothermal technique to cool the air and pass it over the PV panel. The difference in temperature between the ambient and the ground plays a role model in cooling the air.

3.3. *Novel cooling techniques*

Ongoing research in photovoltaic panel cooling has uncovered several innovative methods to reduce the temperature of solar panels and enhance their performance. These strategies include Encapsulated (PCMs), special coatings, heat pumps, heat pipes, thermoelectric cooling, and nanofluids. Each of these cooling strategies offers unique advantages and can significantly improve the performance and longevity of photovoltaic panels.

Nanofluids are a new class of fluids created by incorporating nanoscale materials, such as droplets, nanoparticles, nanotubes, nanofibers, nanorods, nanowires, and nanosheets, into a base fluid. This combination at the nanoscale results in fluids with enhanced thermal properties, making them highly effective for heat transfer applications [48-49]. When smaller nanoparticles are added to the working fluid, they typically result in a greater heat transfer enhancement [50]. Additionally, nanoparticles with lower densities and higher thermal conductivities often achieve faster rates of heat transmission. This improved performance makes nanofluids particularly effective for applications requiring efficient thermal management [51]. Saleh et al. [52]. conducted a numerical investigation on the cooling properties of water and nanofluid in photovoltaic–thermal (PVT) collectors. The use of a 1% volumetric fraction of nanofluids boosts the electric efficiency to 55.45% and the thermal efficiency to 19.5%. Al-Waeli et al. [53] experimented with the integration between PV/T and PCM-nanofluid systems. The results showed that the thermal efficiency improved to 72 %, and the electrical efficiency increased from 7.1% to 13.7%.

Thermoelectric cooling presents an intriguing method for cooling photovoltaic panels by utilizing the Peltier effect to convert excess heat into electrical energy. This technique employs a thermoelectric generator, which generates power based on the temperature differential between the front and back of the panel; a larger temperature difference results in a higher power output. By leveraging this principle, thermoelectric cooling can effectively and passively reduce the temperature of solar cells, enhancing their efficiency. This method can be used independently or in combination with other cooling strategies to further optimize the performance and longevity of photovoltaic systems. According to experiments done passively by Wei Pang et al. [54], the most efficient configuration is a PV/TE with a heat sink that distributes heat by cooling the entire cell by around 8 °C. Furthermore, the cooling performance of the TE module itself is about 27%. In an experimental active procedure, Alireza Akbar et al. [55] used a hybrid photovoltaic-thermoelectric system with a nanofluid. The results showed that using water, SiO₂-H₂O, and Ag-H₂O, respectively, decreased the temperature of PVT-TE by 1.77 °C, 9.76 °C, and 13.17 °C, and increased its efficiency by 13.99%, 16.17%, and 20.68%. This method relies on the absorption and release of energy by a specific fluid within a heat pipe system. The heat pipe facilitates rapid vapor condensation; when heat is applied to one end of the pipe, the internal liquid evaporates immediately and travels to the cooler end of the pipe. This process allows the absorbed heat to be passively dissipated during evaporation, making it an effective cooling solution for solar cells. Theoretically, Shuang-Ying Wu et al. [56] investigate heat pipe photovoltaic/thermal (PV/T) systems. The entire thermal efficiency was 63.65%, according to the results, while the overall electrical and energy efficiencies were 8.15% and 10.26%, respectively.

Integrating heat pumps with solar systems significantly enhances their overall efficiency. By cooling photovoltaic (PV) cells, this integration not only increases the efficiency of energy conversion but also supplies heat energy to the heat pump evaporator. Studies demonstrate that combining heat pumps with PV panels can markedly boost the electrical efficiency of photovoltaic systems. This synergy allows for high generation efficiency and peak power output, making the combined PV and heat pump system a highly effective solution for optimizing energy production and utilization. Jiannan Tong et al. [57] tested a dual-source heat pump and a water-cooled PV/T collector. Results verified that the highest generated power was 827 W, and the highest generation efficiency was 15.3%

Fig. 10 presents an experiment conducted by Fallah Kohan et al. [58] on the performance of a polycrystalline photovoltaic (PV) panel integrated with commercial thermoelectric generators (TEGs). The study employed a three-dimensional numerical simulation to analyze the system's

temperature distribution and evaluate the impact of varying the number of TEGs. The findings revealed that while the hybrid PV-TEG system generated slightly more power compared to a standalone PV panel, the increase was marginal approximately 0.1%. Moreover, the study concluded that implementing an effective cooling system is generally more beneficial than incorporating a PV-TEG hybrid under similar conditions. Additionally, although increasing the number of TEGs enhances power output, the relationship is not linear, indicating diminishing returns with additional TEG units.

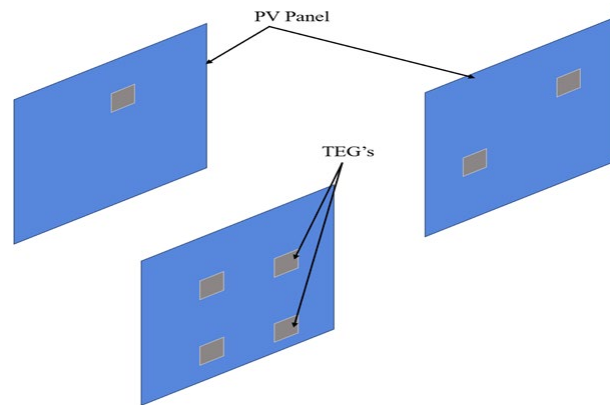


Fig. 10. PV module with TEGs [58].

Hossein Alizadeh et al. [59] conducted a detailed numerical investigation on cooling a photovoltaic (PV) panel using a single-loop pulsating heat pipe (PHP), as shown in Fig 11.

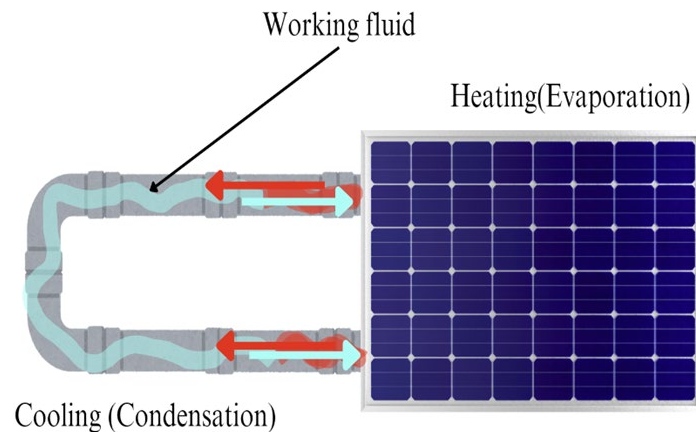


Fig. 11. PV module with heat pipe (single Loop pulsation) [59].

The thermal performance of the PHP system was optimized based on the ideal tilt angle of the PV panel and an optimum working fluid filling ratio of 40%. Numerical simulations were performed to analyze the surface temperature of an uncooled PV panel, with results showing strong agreement with previously published data. Furthermore, a transient simulation was carried out to assess the effectiveness of PHP cooling, revealing a significant surface

temperature reduction of 16.1 K. In contrast, conventional cooling using a copper fin achieved only a 4.9 K reduction. These findings highlight that PHP-based cooling is significantly more effective than solid copper fins in enhancing thermal management. Moreover, the use of PHP technology accelerates the cooling process, minimizes thermal inefficiencies, and improves overall system efficiency in a shorter timeframe. The study also demonstrated that PHP cooling can enhance the electrical power output of the PV panel by up to 18% under a solar irradiation of 1000 W/m², underscoring its potential as an efficient cooling solution for photovoltaic applications.

Hongbing Chen et al. [60] conducted an experimental study shown in Fig 12 to evaluate the energy performance of a hybrid photovoltaic (PV)/heat pump system.

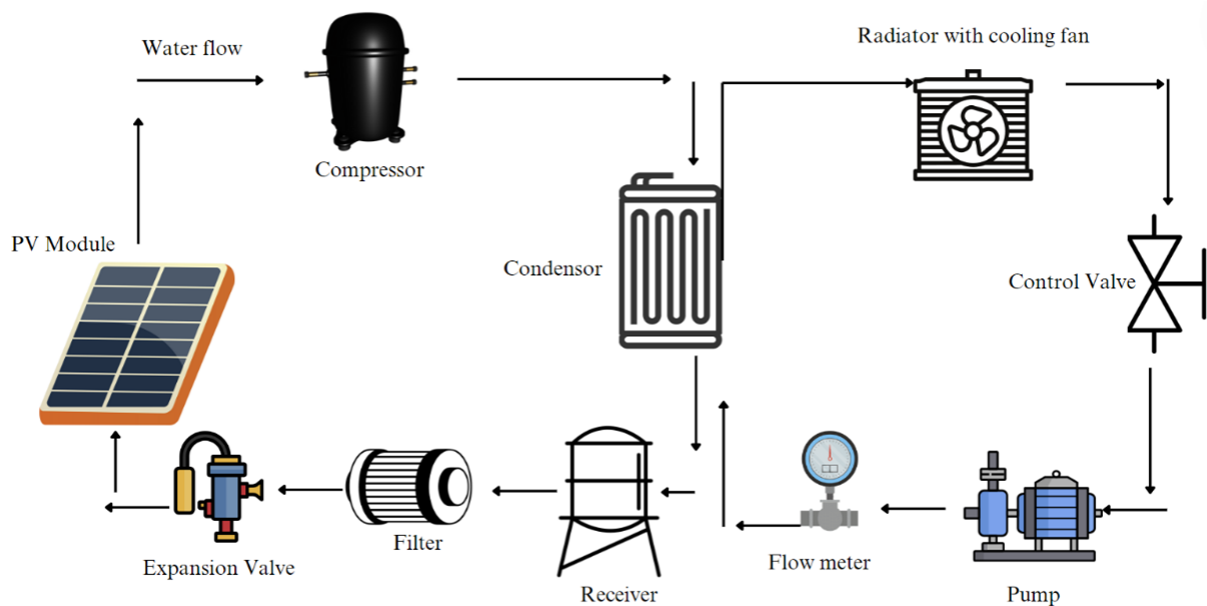


Fig. 12. PV module with heat pipe (single turn) [60].

The research introduced three distinct testing modes to examine the influence of solar radiation, condenser water flow rate, and condenser water supply temperature on the overall efficiency of the heat pump system. The findings revealed that the coefficient of performance (COP) of the heat pump increased with higher solar radiation levels. Additionally, the integration of the heat pump's cooling effect improved the electrical efficiency of the PV panel by up to 1.9% compared to an uncooled PV system. However, the study also determined that variations in the condenser water flow rate had minimal impact on the PV panel's power output and overall electrical efficiency.

4. Water Cooling methods

Water cooling is a highly effective method for enhancing the performance of solar systems, leveraging water's excellent heat absorption properties. This technique significantly improves temperature regulation and overall efficiency of photovoltaic (PV) systems by efficiently dissipating excess heat. Water cooling can be implemented through passive or active cooling approaches, providing versatile solutions to meet various requirements. This method not only boosts the energy conversion efficiency of PV cells but also contributes to their longevity and reliability, making it a valuable strategy in the optimization of solar energy systems.

The following section of this paper will provide a detailed discussion and summary of water-cooling methods for photovoltaic (PV) systems employed over the past 5-6 years. This review will cover advancements in these techniques, installation methods, and their effectiveness. Additionally, it will include an overview of the key researchers and their contributions to this field.

Water is frequently utilized in liquid-based photovoltaic panels for cooling due to its availability, affordability, superior heat capacity, and thermal conductivity. Hydro-based (water-based) cooling methods are classified into two types: passive and active cooling. Passive cooling relies on natural convection, while active cooling requires mechanical pumping to circulate water, enhancing convective heat transfer. Although active cooling improves heat dissipation through increased water flow velocity, the power consumption of the pumps raises operating costs. Furthermore, since the energy used for pumping is subtracted from the total output power of the PV panel when calculating efficiency, optimizing the design, selection, and operation of the pumping system is crucial. This section will focus exclusively on water-cooling methods for photovoltaic cells without considering any integration into water photovoltaic systems. It will explore various water-cooling techniques and highlight the contributions of researchers in this domain. The most used water-cooling techniques are illustrated in Fig 13.

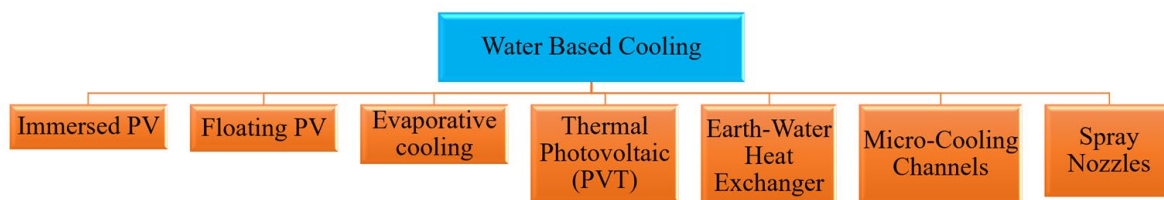


Fig. 13. Water Based Cooling methods for photovoltaic panels.

4.1. Immersed PV

Numerous efforts have been made to identify effective cooling technologies by examining the performance of solar cells under various cooling solutions and methods. One notable approach involves using water as the coolant in immersion cooling. This method entails submerging the photovoltaic cells in water, as shown in Fig 14, significantly enhancing their thermal regulation and overall efficiency. An industrial photovoltaic panel submerged in water gains efficiency for two primary reasons [61]:

- **Absence of thermal drift:** The constant cooling provided by water prevents temperature fluctuations, ensuring stable performance.
- **Reduced light reflection:** The lower refraction index of water minimizes light reflection, allowing more sunlight to be absorbed by the panel.

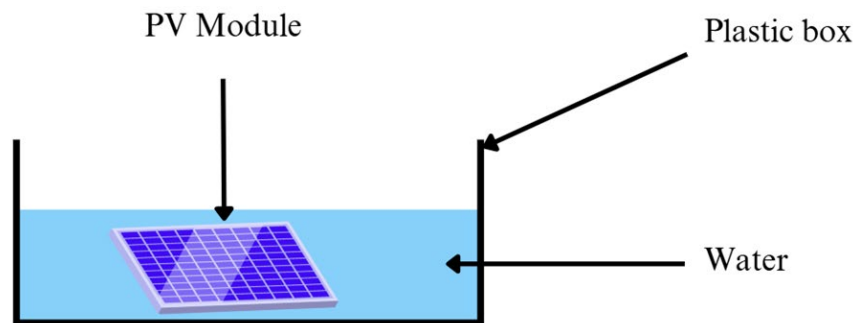


Fig. 14. Experimental setup of a PV cell immersed in water [62].

Table 3 presents research by some scholars investigating the effects of submerging photovoltaic panels in water at different depths to determine the optimal immersion depth for maximum efficiency. The studies demonstrate that water immersion, especially at shallow depths, significantly improves the efficiency of PV panels by maintaining lower operating temperatures. Specifically, the cooling effect varies depending on the depth of submersion, with a notable efficiency boost in the 1 cm to 4 cm range, while deeper immersion (e.g., 40 cm) can reduce efficiency.

Cooling technique	Results	Reference
PV cell is placed inside a plastic box of depth 10.8cm, in which water is the immersed fluid	Under 1 cm of water, the electrical efficiency of the panel increased by a maximum of 17.8%	[62]
Submerging the photovoltaic panel in water at different depths	PV panels operate efficiently when submerged in shallow water, with an increase in power ranging from 10% to 15%. The photovoltaic efficiency increased by about 15% at a water depth of 4 cm.	[63]
Immersing the PV panel in shallow water at different water depths	The efficiency increased by about 15% at a water depth of 4 cm. The optimal water depth was found to be around 3-5 cm for maximum power enhancement.	[64]
Investigated the use of water immersion cooling for photovoltaic (PV) cells in a high concentration system, employing a 250x dish concentrator with de-ionized water for cooling	The system could maintain the PV module at temperatures below 50°C under 940 W/m ² irradiance, with uniform temperature distribution	[65]

Table 3: Works on immersing PV cell in water.

4.2. Floating PV

Only a few demonstrator projects of floating photovoltaics are operational worldwide, with no commercial deployments yet [66]. This innovative concept involves installing solar systems on various water bodies, including lakes, lagoons, vineyards, fish farms, wineries, irrigation ponds, wastewater treatment plants, dams, canals, and oceans, as shown in Figure 15.

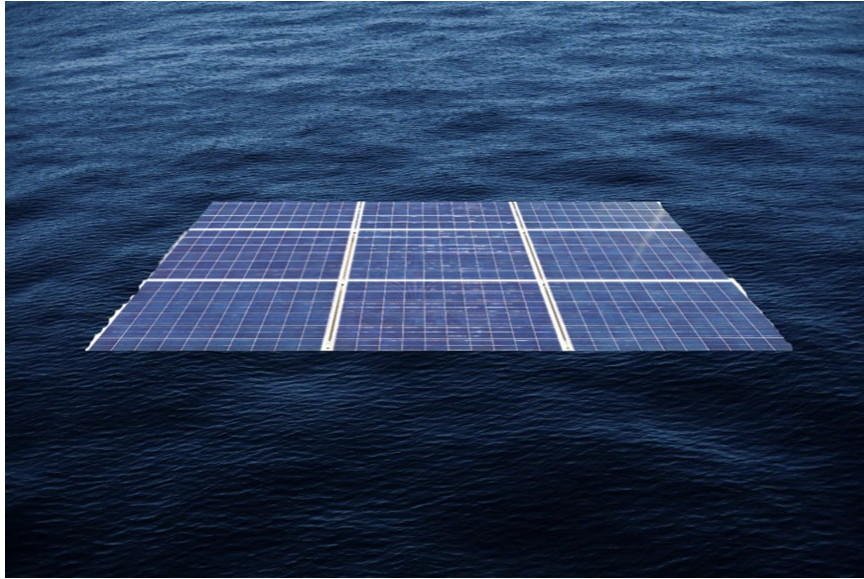


Fig 15. Floating PV cell.

The conversion efficiency of a PV module can vary from 4% to 18% of the incident solar energy, depending on the type of solar cell used and the prevailing weather conditions [67-68]. Due to the cooling effect of water, PV systems installed on water surfaces benefit from significantly lower ambient temperatures. This results in floating solar panels having an average efficiency that is 11% higher compared to ground-mounted solar panels [69].

Floating solar panels offer multiple advantages, including a built-in cooling system that enhances energy production and efficiency. By providing shade to the water beneath, they also help reduce water evaporation. As noted by Nisar et al. [70] and Hafeez et al. [71], positioning solar PV systems above water surfaces can significantly reduce water evaporation, potentially decreasing it by as much as 28%. This strategic placement not only conserves water resources but also enhances the efficiency of solar energy generation by taking advantage of the cooling effect provided by the water.

However, it's important to recognize that ocean environments are not always calm, and strong currents can pose significant risks to floating photovoltaic structures. Consequently, research and development efforts focused on enhancing the durability and resilience of FPV systems in harsh maritime conditions are crucial. Currently, China and the United Kingdom are at the forefront of structural studies to design FPV systems capable of withstanding these challenging environments, driving innovation in this emerging field [72].

Nisar et al. [70] found that at a 0° tilt angle, mono-crystalline and poly-crystalline floating photovoltaic (FPV) panels generate 35.9% and 27.5% more energy, respectively, compared to

their land-based counterparts (LPV). Additionally, Nisar suggests that by optimizing design and factoring in local meteorological conditions, an extra 10% to 17% increase in performance can be achieved. Shatil et al. [73] conducted a study on a 400 W floating photovoltaic (FPV) system with a tilt angle of 0°. After thirteen hours of analysis, the results revealed that the FPV system achieved an average power output of 3.25% higher than its ground-mounted equivalent. Table 4 presents the research by some scholars highlighting the performance improvements of floating photovoltaic (FPV) systems in comparison to traditional PV systems. The key results indicate that FPV systems, where PV modules are placed in direct contact with water or near water surfaces, show several advantages:

- **Efficiency Improvement:** FPV systems demonstrated increased power generation ranging between 1.13% to 5-7% compared to air-cooled and land-based systems.
 - **Temperature Reduction:** The cooling effect of water led to a reduction in PV module temperatures, with temperature decreases observed in the range of 2.74°C to 10°C. This reduction in temperature contributes to the overall efficiency and stability of the PV modules.
 - **Energy Production Increase:** Regarding daily energy output, FPV systems showed enhancements, generating up to 2.33% more energy per day and achieving an average power production increase of up to 11.89 W compared to land-based PV systems.
- These results underline the effectiveness of FPV systems in enhancing power output and reducing operational temperatures, making them a viable alternative to traditional PV installations, particularly in regions where water surfaces are accessible.

Table 4: Works in the field of floating photovoltaic panels.

Cooling technique	Results	Reference
Photovoltaic (PV) modules are strategically placed horizontally on a floating membrane, allowing for efficient heat exchange between the modules and the underlying water.	The PV string that was in direct contact with water had an average that was 5-7 percent higher than the air-cooled string	[74]
A test bench with an established measurement station with FPVS and OPVS components has been presented.	Throughout the testing period, the average temperature of the (FPV) modules remained consistently lower than that of the (OPV) modules, with temperature differences reaching up to 2.74°C. Moreover, the FPV system demonstrated superior performance, generating up to 2.33% more energy per day compared to the OPV system.	[75]
A one-month investigation was conducted on a 100 W polycrystalline floating photovoltaic (FPV) system installed over the brackish waters of Sungsang in Sumatra.	The study revealed that, compared to their land-based photovoltaic (LPV) counterparts, the floating photovoltaic (FPV) system achieved an average power production increase of 11.89 W while also experiencing a significant temperature reduction of up to 4.7°C.	[76]
eight FPV systems with tilt angles ranging from 5 to 12 were mounted for thermoelectric performance and structural research.	The temperature of the floating photovoltaic (FPV) system was found to be reduced by 5 to 10°C compared to standard systems. Additionally, the FPV system exhibited a mean performance ratio that was 5 to 10% higher than that of a conventional rooftop installation	[77]
A one-month trial was conducted in Jodhpur, India, using a 250 W polycrystalline photovoltaic module positioned at a 23° tilt	They discovered that the FPV system's maximum power generation is 1.13% greater than the LPV systems.	[78]

4.3. *Spraying Nozzles*

In developing countries, photovoltaic technology is frequently employed for water pumping, offering significant potential for driving social and economic progress. Given that photovoltaic cells are the core components of a PVPS, fluctuations in their power output can directly affect the overall performance of the system. Ensuring high efficiency is, therefore, a key goal for PVPS designers. To achieve this, researchers have explored and proposed various strategies for optimizing PVPS design, aiming to enhance system efficiency while reducing installation costs [79].

The water spray cooling system, as shown in Fig. 16, has been shown through studies to be successful in reducing the temperature of solar panels and can boost their performance [80].

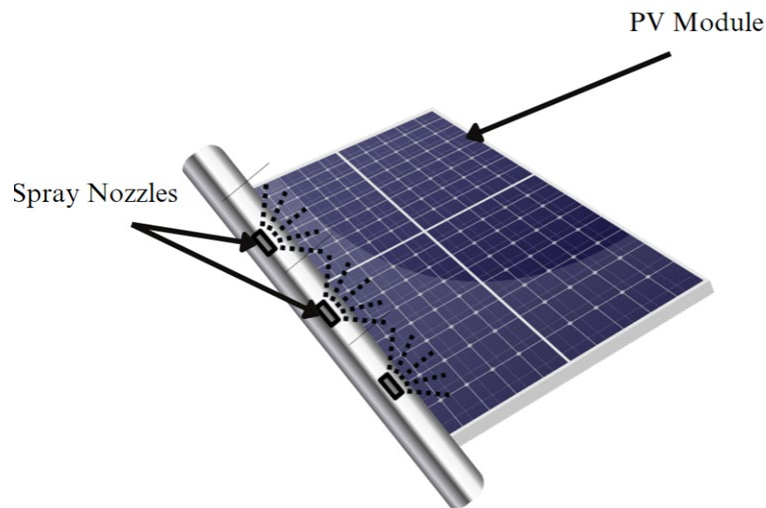


Fig 16. Spray nozzle cooling of PV [90].

To optimize the effectiveness of a water spray cooling system for photovoltaic (PV) panels, several key factors must be carefully adjusted. These include the number of nozzles, the type of nozzles used, the water pressure, the spray rate, the duration of each spray, and the positioning of the nozzles [81-82]. In addition, the choice of nozzles in a water spray cooling system is a critical factor that significantly influences the overall cooling performance.

The type of nozzle determines the spray pattern, droplet size, and distribution, all of which are crucial for achieving uniform and effective cooling across photovoltaic (PV) panels.[83]. Moreover, the dispersion characteristics of the water spray, including the spray pattern and angle, are directly influenced by the specific nozzle specifications chosen for the cooling system. These features, in turn, play a crucial role in determining the cooling effectiveness of the system.[84].

However, using spray nozzles in a water-cooling system for photovoltaic (PV) panels comes with several drawbacks, including potential corrosion, mineral deposits, and water consumption. In summary, while spray nozzles can enhance the performance of PV panels by reducing their operating temperature, these benefits must be weighed against the potential disadvantages, particularly in terms of maintenance, sustainability, and long-term system costs. Laseinde et al. [85] used a spray water system functioning at 80ml/s, which caused efficiency to increase by 16.65%. Hadipour et al. [86] implemented a water spray cooling system on solar panels that significantly reduced the panel's temperature from 63.95°C to 33.68°C. This substantial temperature drop significantly increases the panels' efficiency, boosting it by 33.3%.

Table 5 presents the research conducted by some scholars who investigated the effects of the cooling method spray nozzles on its efficiency. The table presents the effectiveness of water spray cooling systems on photovoltaic (PV) modules, focusing on temperature reduction and efficiency improvements:

- **Temperature Reduction:** The application of water-spray cooling resulted in temperature drops ranging from 5°C to 23°C. In specific cases, temperature reductions were as high as 12.31°C and even up to 10°C under certain conditions.
- **Efficiency Improvement:** The cooling effect led to increases in photovoltaic efficiency, with gains ranging from 1.1% to 16.3%. Power output also benefited, with increases in energy generation between 7.7% and 14.3%. Additionally, the open-circuit voltage saw improvements, with increases of up to 6.06%.

Overall, the implementation of water spray cooling systems on PV modules substantially enhances both temperature management and energy efficiency, indicating its potential as a viable method for improving photovoltaic performance under high-temperature conditions

Table 5: Work in the field of cooling photovoltaic panels using spray nozzles.

Cooling technique	Results	Reference
Water spray cooling system	The temperature dropped from 45°C to 35°C and efficiency rose by 14.3%	[87]
Spray nozzles between the front and back side	Compared to the cooling system, there was a 1.93 % increase in power conversion efficiency and a 6.06 % rise in open-circuit voltage.	[88]
Water-spray cooling system	5 to 23 °C drop in temperature and a 9 to 22% gain in power.	[89]
Water-spray cooling technique	A maximum total increase of 16.3% (effectively 7.7%%) in electrical energy output and a total increase of 14.1% (effectively 5.9%%) in the photovoltaic panel's electrical efficiency	[90]
Spray cooling is composed of multiple lengths of support and guide plates on the PV module's back surface	Compared to the non-spray system at ambient temperatures ranging from 31 to 41 °C and relative humidity of 45%, the photovoltaic (PV) cooling system achieved an average reduction in cell temperature of 12.31 °C. This temperature decrease led to an average efficiency improvement of 1.10%.	[91]

4.4. Evaporative cooling (EC)

Evaporation occurs when the mass of the fluid transits from a liquid to a vapor state at temperatures below the boiling point. This process is driven by a concentration gradient, similar to other mass transfer phenomena, where molecules naturally move from regions of higher concentration to regions of lower concentration. Evaporation efficiency is further enhanced by fluid movement, which helps to continuously replace the high-concentration layer near the surface with fresh, lower-concentration fluid, facilitating a more effective mass transfer [92]. Moreover, when a small amount of coolant undergoes a phase transition from liquid to vapor, evaporative cooling (EC) occurs, effectively removing excess heat from the surface [93]. For example, as water evaporates, it absorbs heat from its surroundings, creating a cooling effect. This natural cooling mechanism can be effectively utilized to lower the temperature of photovoltaic (PV) panels [92]. This process illustrates latent heat cooling, where water vapor in the surrounding air reaches equilibrium through evaporation, generating a cooling effect [92]. Evaporation is primarily influenced by factors such as air temperature, air velocity, relative humidity, and the surface area exposed to the air. These variables typically interact to regulate

both the cooling effect and the overall rate of evaporation [95]. In addition, Evaporative cooling (EC) systems have limited cooling capacity in humid conditions due to the air's near saturation, making them less effective and unsuitable for such environments [94].

However, this cooling method is simple, cost-effective, sustainable, efficient, and environmentally friendly. It performs exceptionally well in dry, warm climates, making it highly promising for regulating the temperature of photovoltaic panels installed in hot, arid regions [92-94-96-97-98].

Evaporative cooling systems can be done through several methods, for example, EC systems utilizing synthetic clay, EC systems using cotton wicks, EC systems using co-current configurations, PV evaporative chimney, EC systems using cloth and rubber pipes, EC systems using zeolite, EC cooling systems with porous layer, EC system utilizing water from an underground tank, EC system with an atmospheric water harvester, and so many ways as classified lately by M.Cengiz et.al [99].

Using synthetic clay of various thicknesses, Alami [93] constructed a passive EC system to regulate the rise in temperature of PV modules and investigate the effects of cooling on the modules' efficiency. It was stated that the module's temperature might be lowered by 40°C during midday, the peak solar period. During solar noon, there was an average 15.7% rise in output power and a 16.7% increase in output voltage. Haidar et al. [92] used cloth and rubber tubes that were immediately attached to the back of the cooled PV panel and left open to the surrounding air. The results showed that the PV panel's temperature significantly decreased by more than 20°C) compared to the reference panel, and its electrical power generation increased by about 14%. Alktrane and Bencs [100] investigated an EC method that coated the PV panel's rear side with water-immersed cotton wicks, as shown in Fig 17.

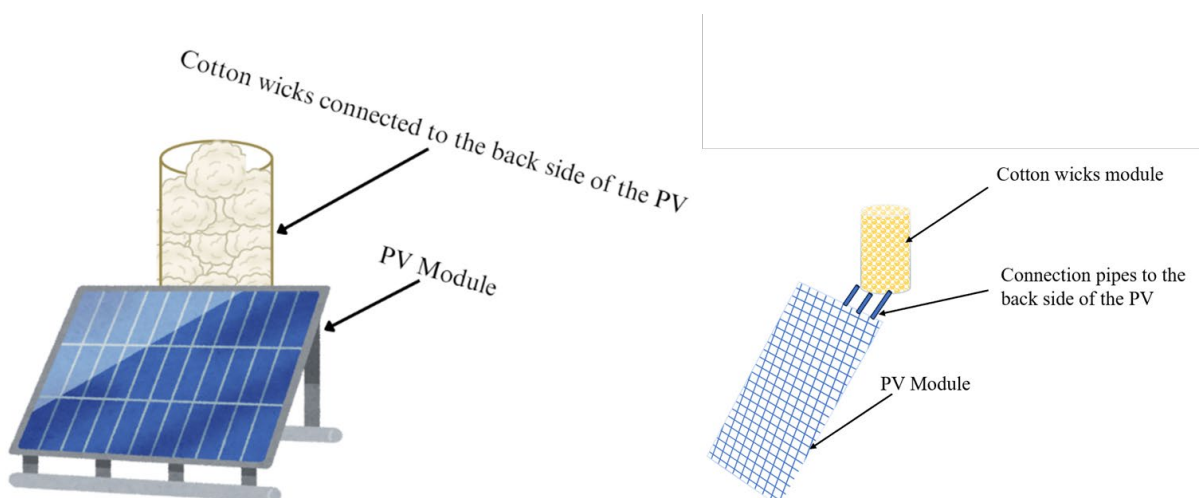


Fig.17. Evaporative cooling using cotton wicks connected to the back side of the PV module (a), side view for the experiment (b). [101].

Results showed that the panel's efficiency had increased by 53%, with a 10.2 °C decrease in temperature.

Table 6 summarizes the effectiveness of evaporative cooling (EC) systems on photovoltaic (PV) panels, highlighting temperature reductions and improvements in power output and efficiency:

- **Temperature Reduction:** EC systems, utilizing materials like cotton wicks, cellulose Fibers, and hydrophilic pads, resulted in temperature decreases ranging from 10% to 46%. Specific reductions in panel temperature ranged from 17.5°C to as high as 22.3°C.
- **Efficiency and Power Output Improvement:** The electrical efficiency of PV panels improved by 8.7% to 11.3%, while electricity production increased by up to 9.6%. In some cases, passive cooling methods led to power output increases as high as 73%, with potential efficiency boosts approaching 97.6%.

In summary, using EC systems significantly lowers the operating temperatures of PV panels, leading to notable improvements in efficiency and power generation, with passive cooling methods showing some of the most significant enhancements.

Table 6: Experimental studies on Evaporative Cooling of PV modules.

Cooling technique	Main findings	Reference
EC System Using Cotton Wicks and water as a coolant (Passive cooling)	Temperature decreases by 3°C-26°C in PV modules An increase in electrical efficiency of 11.3%	[101]
EC Using Cotton-Cellulose Fiber passive water cooling	Reduced temperature of PV panels by up to 20 °C An increase in PV panel electricity production of up to 9.6%	[102]
EC in a Back-Mounted Chimney-like Channel using water as a coolant (active cooling)	A maximum drop in temperature of 17.5 °C and an improvement in power output of 8.7% for PV modules.	[103]
EC System Utilizing Cotton Wicks Immersed in Pure Water (passive cooling)	A convenient drop in PV panel temperature A 73% increase in the power output of PV panels It is possible to boost PV panel efficiency by about 97.6%.	[104]

EC Using a Hydrophilic Pad Made of a Mixture of Polypropylene and Synthetic Fiber using water as a coolant (active cooling)	When the module's temperature rises above 70 °C, there is about a 27.2 °C temperature drop, which causes an increase in electrical generation of 10%	[105]
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4.5. Thermal photovoltaic (PVT) cooling

Hybrid solar photovoltaic thermal (PVT) panels integrate thermal collectors with photovoltaic modules, simultaneously generating heat and electrical energy. This dual-function system not only maximizes energy output but also significantly improves overall efficiency. By capturing and utilizing the waste heat generated by the PV cells, these panels help to cool the surface of the photovoltaic system, thereby enhancing the electrical efficiency of the solar cells. This innovative approach optimizes the use of solar energy, making PVT panels a highly efficient and versatile solution for renewable energy generation [106].

Although liquid PVT collectors have lower sun-to-electricity and sun-to-heat conversion efficiencies compared to separate photovoltaic and solar-thermal panels, they can generate up to 40% more energy due to the synergies achieved through integration. This increased efficiency makes PVT systems particularly advantageous in scenarios where both heat and electricity are required simultaneously. They are especially suitable for installations on small or structurally delicate roofs, where space constraints make it impractical to deploy separate PV and solar-thermal arrays side by side. The ability to combine these functions in a single system optimizes energy production and offers a practical solution for maximizing the use of available space [107].

The fundamental operation of a PVT system can be described as follows: Sunlight enters the PV/T system and is absorbed by the PV cells, which convert the solar energy into direct current (DC) electricity, as illustrated in Figure 18.

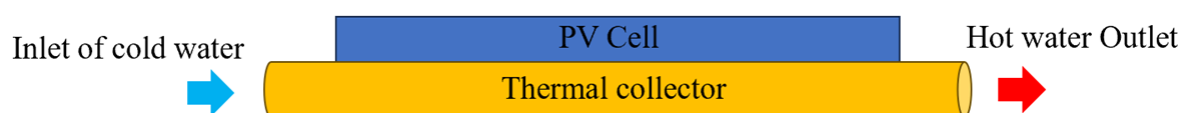


Fig. 18. Photovoltaic thermal collector.

Simultaneously, the excess heat generated by the PV cells is transferred to the cooling fluid circulating within the system. This heat transfer process not only boosts the electrical efficiency

of the PVT system by reducing the temperature of the PV cells but also heats the cooling fluid, making it a dual-purpose solution for generating both electricity and thermal energy [108].

Various cooling channel designs, including porous, converging, double-channel, and others, play a significant role in influencing the performance of PVT systems. Each design offers unique advantages that can enhance heat dissipation, improve thermal management, and optimize overall system efficiency, depending on the specific application and environmental conditions.

Recently, Arman et al. [109] introduced an innovative approach to enhance the efficiency of Photovoltaic-Thermal systems with forced water circulation. Their analysis demonstrates significant efficiency improvements, with gains ranging from 0.8% to 1% at water flow rates of 2, 2.25, 2.75, and 3 Liters per minute. This method not only increases the electrical output but also contributes to a higher overall system efficiency, making it a promising advancement in PVT technology. Kamal Singh et al. [110] used a reference photovoltaic panel and photovoltaic polycrystalline silicon with water PVT system employing a single copper absorber in their experiment. The results showed that electrical efficiency increased by 6.08%, and the temperature was reduced by 15.23% at a mass flow rate of 0.0166 kg/s.

Table 7 summarizes various water-based cooling techniques applied to photovoltaic/thermal (PV/T) systems, highlighting improvements in both electrical efficiency and temperature reduction:

- **Efficiency Improvement:** The panel efficiency increases ranged from 8.08% to as high as 36.1%. Additionally, some systems demonstrated total efficiency improvements of up to 84.4%, depending on both empirical and numerical data.
- **Temperature Reduction:** The cooling techniques resulted in significant temperature drops, with reductions ranging from 71.2°C to 45.1°C.
- **Electricity Production Gains:** In terms of total electricity generated, improvements ranged up to 29% when comparing cooled PV/T systems to uncooled ones.

Overall, water-based cooling techniques for PV/T systems offer substantial gains in efficiency and temperature management, with increases in performance directly correlating with effective thermal control.

Table 7: Some research on photovoltaic panels with water cooling for PT.

Cooling technique	Main findings	Reference
Theoretically investigated the cooling of PV/T panels using a porous structure.	Panel efficiency was increased by 8.08 %	[111]
Investigated numerically and experimentally cooling by water a PV/T with a convergent cooling channel	The maximum percentage rise in the conversion of electric efficiency was 36.1 %, and the temperature decreased from 71.2 to 45.1 °C	[112]
PV/T with water cooling system	When compared to uncooled PV, the total generated electricity increased by around 29%.	[113]
Investigated numerically and experimentally cooling by water a PV/T with a parallel plate cooling channel	The highest possible total efficiency of the PV/T system has been estimated to be 84.4% and 80%, respectively, depending on both empirical and numerical data.	[114]
Investigated Experimentally a PV/T with a transparent collector to use both bifacial PV module	The electrical efficiency is estimated at 16.4 %	[115]

4.6. Geothermal

Due to the earth's high thermal capacitance, geothermal systems are commonly used to exchange thermal energy. One of their key applications is in air conditioning systems, where they effectively dissipate excess heat. This concept can also be extended to the cooling of photovoltaic (PV) systems, where geothermal cooling can help manage temperatures, enhancing efficiency and prolonging the panels' lifespan.

The geothermal cooling principle is based on the fact that at a burial depth of at least 3.5 meters, the temperature of the soil remains remarkably stable throughout the year. This consistent temperature closely aligns with the average annual ambient air temperature, providing a reliable and efficient means of cooling [116]. By leveraging this natural stability, geothermal systems can maintain a nearly constant temperature, independent of surface weather conditions, making it an effective and energy-efficient cooling method.

An earth-water heat exchanger is utilized due to water's superior heat transfer capacity. Water's ability to absorb and transfer heat efficiently makes it an ideal medium for exchanging thermal energy with the surrounding earth. This high heat transfer capacity enhances the system's overall effectiveness, allowing it to maintain consistent temperatures and improve the efficiency of cooling processes.

This system's pipes are buried at a specific depth below the surface to convey hot water. These pipes act as heat exchangers, facilitating heat transfer from the hot water to the surrounding earth. As the water flows through the pipes, its temperature is gradually reduced as heat is dissipated into the cooler soil, effectively lowering the water's temperature before it exits the system [117].

Through the reading of most articles, we expect that geothermal systems are environmentally friendly and sustainable. They use the Earth's natural temperature as a cooling source, which reduces reliance on external energy for cooling purposes. In addition, geothermal systems can operate efficiently throughout the year, providing consistent cooling even in varying weather conditions. However, installing a geothermal heat exchanger system is expensive, involving significant upfront costs for drilling, piping, and installation, and requires regular maintenance to ensure efficient operation.

Sanjeev Jakhar et al. [118] Investigated experimentally an integrated photovoltaic thermal solar (IPVTS) system with an earth-water heat exchanger (EWHE) as shown in Figure 19.

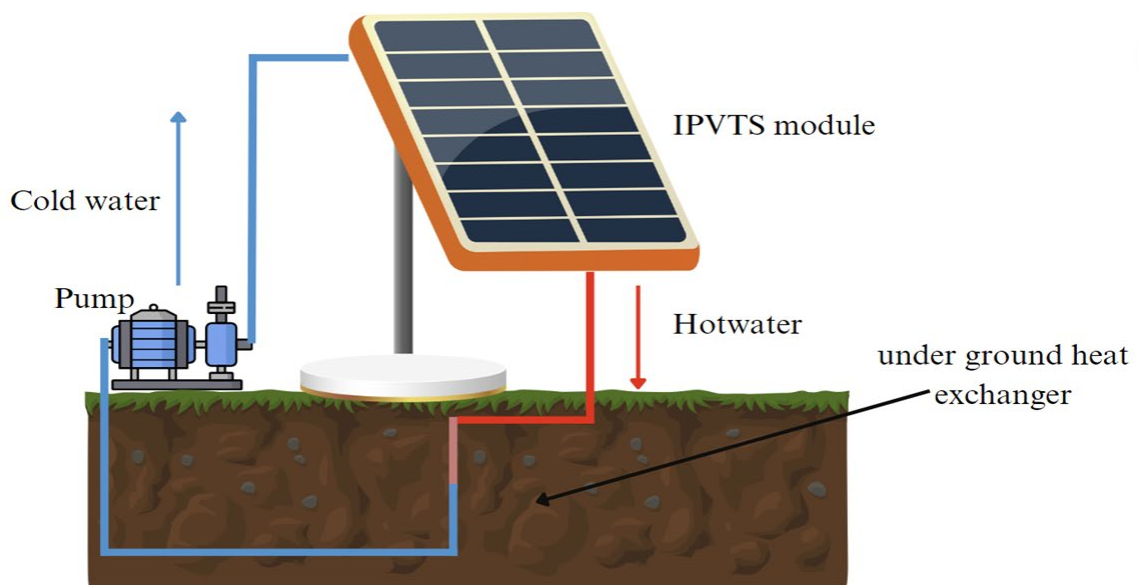


Fig. 19. EWHE cooling for photovoltaic thermal solar module. [118].

This study showed that the electrical efficiency increased by 1.02%-1.41% compared to the uncooled condition. In addition, a numerical study done by Ruoping et al. [119] examined the efficiency of geothermal exchange-cooled photovoltaics in arid climates. Comparing the results with standard PV systems, and after calculation, the panel temperature decreases on average by 3 °C, for every 1 m/s increase in wind speed, resulting in an annual electricity yield of 7.9%. Table 8 presents the research conducted by some scholars who investigated the effects of the evaporative cooling method. Table 8 presents the research conducted by some scholars who investigated the effects of the evaporative cooling method applied to PV and PV/T systems and their impact on temperature and efficiency:

- **Temperature Reduction:** Cooling techniques achieved significant temperature decreases. For PV modules, temperatures were reduced by up to 30%, while geothermal pre-cooled water flow systems brought the temperature down from 72.5°C to as low as 39.3°C. For CPV/T systems, the maximum temperature was reduced from 416.36°C to 85.28°C under specific flow conditions, while other systems demonstrated reductions from 73°C to around 43.68°C to 49.64°C.
- **Efficiency Improvement:** Power output improvements ranged up to 11% for some PV systems, while electrical and thermal efficiencies for PV/T systems ranged from 8.26% to 8.52% and 44.06% to 55.45%, respectively.

In summary, these methods significantly reduce operating temperatures, enhancing both the power output and efficiency of PV and PV/T systems, particularly under high-irradiance conditions.

Table 8: Some research on photovoltaic panels with Earth water Heat exchanger cooling.

Cooling technique	Main findings	Reference
Designed an active water cooling system consisting of an open-loop water-based heat exchanger mounted on the rear surface of the CPC-PV module	Comparing the module to the uncooled CPC module, the temperature was lowered by 30%, and the power output increased by 11%.	[120]
Investigated experimentally the performance of a V-trough PV concentrator integrated with a buried water heat exchanger BWHE cooling system	The panel surface temperature is reduced from 72.5 °C without cooling to 47.2 °C, 45.5 °C, 41.8 °C and 39.3 °C with geothermal pre-cooled water flow rates of 0.01 kg/s, 0.02 kg/s, 0.03 kg/s and 0.04 kg/s, respectively	[121]

Simulation of CPV/T system with EWHE	The maximum temperature of CPV is reduced from 416.36 °C to 85.28 °C for the mass flow rate of 0.022 kg/s	[122]
Analyzed the performance of PV/T systems integrated with Earth Water heat exchanger cooling and glazed tubes both theoretically and experimentally	The cooling module's temperature ranged from 43.68 to 49.64 °C, while the uncooled module's temperature was captured at 73 °C. The electrical and thermal efficiencies were found to be between 8.26 and 8.52 % and 44.06 and 55.45 %, respectively	[123]

4.7. *Microcooling channels and Pipes*

Being the centerpiece of the system, the cooling channels effectively dissipate heat from the solar modules using a working fluid [124]. Because of their compact design and excellent heat transfer efficiency, micro-channel heat exchangers have found widespread application.

Micro-channel solar collectors offer several advantages, including higher collector efficiency, reduced volume and weight, and lower manufacturing costs [125]. Additionally, their flat surface design allows them to integrate seamlessly with photovoltaic modules, enhancing overall system performance. The PV/T collector makes extensive use of parallel cooling channels because of their low-pressure drop and affordability [126-127].

When comparing the flow boiling heat transfer of refrigerants in micro-channels to larger diameter round tubes, the smaller one is substantially higher [128]. As a result, the system's overall efficiency is closely tied to the thermal performance of these cooling channels [129-130]. In conclusion, the implementation of cooling channels has proven to be an effective strategy for maintaining optimal thermal performance in photovoltaic cells.

In recent years, research on integrating microcooling channels with PV panels has attracted the attention of researchers. Modjinou et al. [131] use microchannel heat pipes to improve heat transfer inside the PV/T system, which successfully lowered the temperature of the PV panels. The results showed that the average collector efficiency, average electrical efficiency, and combined efficiency of the PV/T system are, respectively, 27.75 %, 7.78 %, and 35.53 %. In addition, Zhou et al. [132] used an MC-PVT-SC to construct a solar direct-expansion heat pump system. They also installed an insulation layer, connected the microchannel to the photovoltaic module, and conducted theoretical and experimental research on the system's COP, electric efficiency, collector efficiency, and overall efficiency under real-world operating conditions. These factors yielded results of 55%, 13.7%, 69.1%, and 5.0, respectively.

Moreover, Chaoqun Shen et al. [133] designed a theoretical model with different microcooling channels, as shown in Figure 20.

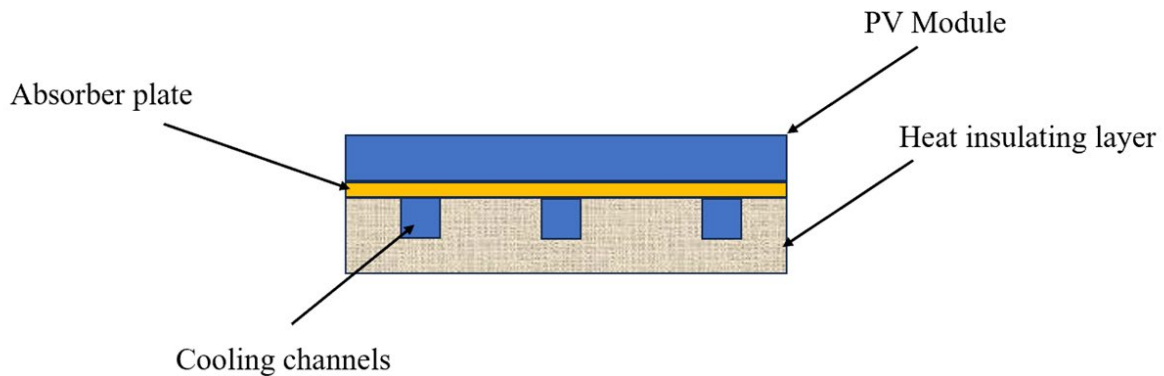


Fig. 20. Schematic of the PV/T collector with parallel cooling channels [133].

The numerical results reveal that when the number of subchannels is set to 10, the cooling channels experience the lowest pressure drop. Additionally, the temperatures of the photovoltaic modules remain low and evenly distributed. The I-type configuration for the inlet and outlet is identified as the optimal choice, as it results in minimal pressure drop and excellent thermal performance of the PV/T collector. As the diameter ratio between the main channel and subchannels increases, the temperature of the photovoltaic modules decreases and becomes more uniformly distributed.

Table 9 presents the research conducted by some scholars who investigated the effects of cooling channels on the PV module, highlighting their impact on power and efficiency improvements:

- **Power Increase:** Several cooling techniques, including microchannel and water pipe systems, led to power improvements. The increase in maximum power output ranged from over 30% to as high as 47%, depending on the specific cooling method used.
- **Efficiency Gains:** Electrical efficiency saw notable improvements across different techniques. Increases ranged from 6.08% to 38.4%, with the highest gains occurring in systems using helical and straight aluminum microchannels.
- **Heat Dissipation:** Multi-header microchannel systems eliminated around 19% more heat compared to single-header systems, resulting in a 28% increase in electrical power.
- **Temperature Reduction:** One study demonstrated a 15.23% decrease in PV module temperature, which contributed to improved efficiency.

In summary, employing advanced cooling systems like microchannels and water pipes significantly enhances both power generation and efficiency while effectively reducing the operating temperatures of photovoltaic systems.

Table 9: Some research on photovoltaic panels with Micro cooling channels and Pipes.

Cooling technique	Results	Reference
Investigated the operation of an array of rectangular microchannels with a single-phase flow of water.	There was a slight increase in the cell's maximum power of more than 30%.	[134]
Investigated research comparing the cooling of hybrid photovoltaic panels using single and multi-header microchannels.	It was found that the multi-header microchannel eliminated roughly 19% more heat than the single-header microchannel and generated approximately 28% more electrical power.	[135]
Investigated solar cell performance experimentally utilizing straight and helical aluminum microchannels.	For both configurations, the electrical efficiency rose by an average of 17.7% to 31.1 % in the straight channel and by an average of 20–38.4% in the helical channel when the flow rate was raised from 0.25 to 1 L/min.	[136]
Investigated experimentally cooling the PV module by the use of a water pipes cooling system	Under the same cooling conditions, solar photovoltaic efficiency could rise by an average of 47%.	[137]
Investigated experimentally Copper tubes attached behind a conventional photovoltaic panel	The electrical efficiency increased by 6.08 %, and a decrease of approximately 17 °C in the temperature of the PV module	[138]

4.8. *Jet Impingement*

Jet impingement heating and cooling operate by directing a high-velocity stream of a working fluid onto a target surface to enhance heat transfer. This method is highly effective for both heating and cooling applications across a wide range of temperatures. Depending on the specific temperature requirements, various modifications and optimizations can be implemented to improve efficiency, such as adjusting jet velocity, nozzle design, or fluid properties, all of which influence the cooling or heating performance. These enhancements enable jet impingement to be utilized in diverse industrial processes, from electronics cooling to thermal processing in manufacturing.

Jet impingement occurs when a working fluid is ejected as a high-velocity jet onto a surface, typically one that is heated. These heated surfaces often have a known heat flux, and the resulting temperature change is carefully measured to analyze heat transfer efficiency [139]. As the working fluid exits the nozzle, it interacts dynamically with the surrounding environment before reaching the target surface. Depending on the size and mass of the droplets, various aerodynamic effects can occur, including the formation of vortices, curls, or secondary splashes. These fluid dynamics significantly impact the heat transfer rate, making jet impingement a widely studied technique for applications ranging from electronic cooling to high-temperature industrial processes [139].

Javidan et al. [140] investigated the cooling of photovoltaic (PV) modules using a multi-nozzle JIC system with water as the coolant. The results showed that the average PV surface temperature is reduced from 63.95°C to 33.68°C, and a maximum output power enhancement of 47.67%. Moreover, Bahaidarah et al. [141] conducted an experimental study to assess the impact of jet impingement water cooling on the performance of photovoltaic panels. Their findings revealed that, in the absence of cooling, panel temperatures reached 69°C in June and 47.6°C in December. However, with the implementation of jet cooling, the average cell temperature dropped significantly to 36.6°C in June and 31.1°C in December. This cooling method led to substantial performance enhancements. In June, energy output increased by 51.6%, while conversion efficiency improved by 66.6%. Similarly, in December, jet cooling contributed to a 49.6% rise in power generation and an 82.6% boost in conversion efficiency. Additionally, Abdulrasool et al. [142] designed a photovoltaic thermal (PVT) solar collector incorporating water jet collision for enhanced cooling see Figure 21.

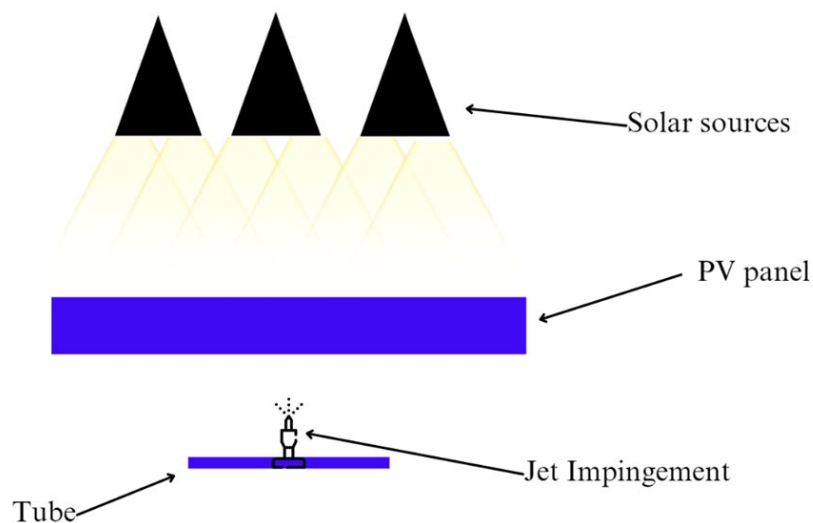


Fig. 21. Schematic of Jet impingement cooling system [142].

Their study found that, at a solar radiation level of 1000 W/m^2 , the system achieved maximum thermal, photovoltaic, and overall PVT efficiencies of 72%, 11.35%, and 81%, respectively.

From this viewpoint, cooling techniques like immersion cooling and floating photovoltaic systems offer significant efficiency enhancements due to their continuous interaction with water and reduced operating temperatures; however, their implementation is constrained by site-specific conditions and structural resilience in turbulent aquatic environments. Spray nozzles and jet impingement methods exhibit swift and significant cooling, rendering them appealing for areas with strong solar radiation; nonetheless, their long-term viability is limited by excessive water usage, scaling, and corrosion challenges. Conversely, evaporative cooling demonstrates remarkable efficacy in arid climates characterised by low humidity but is useless in wet areas where evaporation rates are negligible. Hybrid PVT systems and microchannel cooling have significant integration potential and scalability; nonetheless, they require meticulous engineering, substantial initial investment, and dependable maintenance. Geothermal exchangers, although stable and sustainable, necessitate substantial installation expenses and land availability, thus constraining wider implementation.

The selection of an appropriate cooling method is hence contingent upon local conditions. Floating photovoltaic systems are optimally designed for areas with plentiful inland water reservoirs, whereas evaporative cooling is most effective in arid, high-temperature environments. Geothermal cooling is beneficial when land and drilling equipment are accessible, while microchannel and jet impingement techniques are more appropriate for sophisticated building-integrated PV/T systems. Furthermore, water availability, ambient humidity, solar irradiation, and system scale (residential versus industrial) should be regarded as essential design elements in assessing applicability.

Notwithstanding their potential, numerous implementation obstacles persist. This encompasses guaranteeing material resilience against extended water exposure, tackling water scarcity in specific areas, averting fouling or obstruction in spray and microchannel systems, and reducing parasitic energy expenditure in active cooling configurations. Furthermore, widespread adoption necessitates not only technical enhancements but also cost reductions, standardised designs, and interaction with current photovoltaic infrastructures. Overcoming these restrictions will be essential for transitioning water-based cooling from experimental demonstrations to dependable, large-scale implementations.

5. Innovative Cooling systems integrated with water cooling

Researchers are actively exploring various integrated cooling methods to improve photovoltaic panels' thermal and electrical efficiency. Numerous studies have been conducted to identify the most effective solutions for enhancing the performance of photovoltaic modules. This section will delve into some different integrated water-based cooling techniques that have shown promise in boosting thermal and electrical efficiency.

Elavarasan et al. [143] conducted an experimental investigation combining phase change material (PCM), fins, and water to enhance the cooling of photovoltaic (PV) panels, as shown in Figure 22.

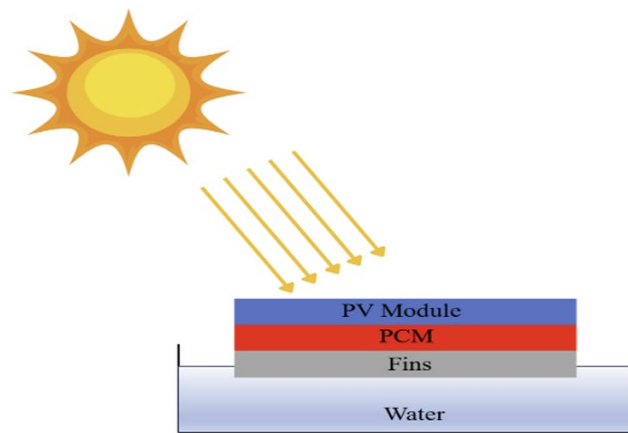


Fig. 22. Schematic of a PV module integrated with PCM and Fins embedded in water [143].

The study aimed to improve the thermal and electrical efficiency of PV panels by leveraging the latent heat of fusion of PCM and water evaporation in a passive cooling configuration. The experimental setup involved two identical polycrystalline PV panels, one equipped with PCM, fins, and still water. The experimental setup was tested under real-time conditions, and the results indicated a significant improvement in the thermal regulation of the PV panels. Specifically, the cooled PV panel's temperature was consistently maintained below 50°C, whereas the uncooled panel reached temperatures as high as 73°C. The proposed cooling configuration resulted in a maximum power enhancement of 20.25% and improved electrical efficiency by 20.13%. The study also projected that this cooling system could lead to annual energy savings of approximately 367 MWh for a 1 MW PV system, with an additional 9.4% reduction in CO₂ emissions compared to standard PV panels.

In addition, Yang et al. [144] conducted an experimental study to enhance the efficiency of photovoltaic (PV) panels by integrating a spray cooling system with a shallow geothermal energy heat exchanger, as shown in Figure 23.

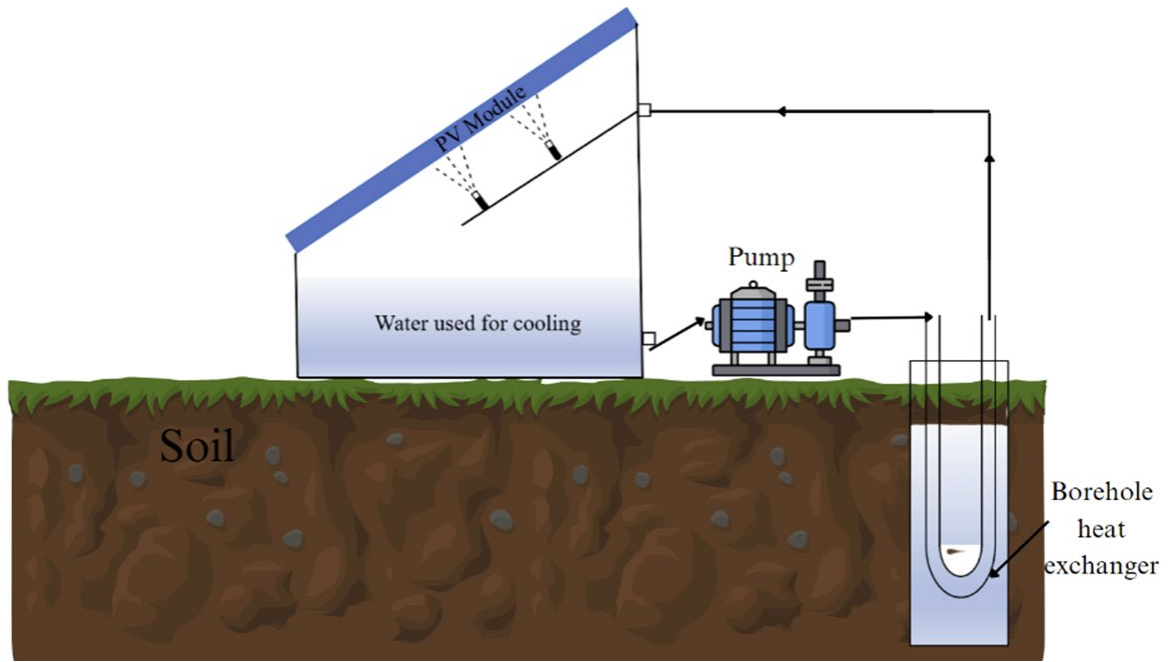


Fig. 23. PV module integrated with Spray nozzles and a Geothermal Heat exchanger [144].

The method involved cooling the PV panel by spraying water onto its reverse side, then recycling the water through a U-shaped borehole heat exchanger (UBHE) installed in an existing well, which exchanged heat with shallow geothermal energy. The experiments were performed in three stages: first, the panel operated without any cooling system; second, with the cooling system but without the UBHE; and third, with both the cooling system and UBHE. The results showed that the cooling system significantly improved the panel's efficiency, particularly when combined with the UBHE. The efficiency increased by 14.3%, and the system's cost could be recovered in 8.7 years. The study demonstrates the potential of using geothermal energy in conjunction with water cooling to maintain optimal PV panel temperatures, thereby enhancing their performance.

Moreover, Mahmood et al. [145] investigated a hybrid photovoltaic evaporative cooling (PV/EC) system designed to enhance the efficiency of photovoltaic panels under arid conditions. The cooling method utilized involves an evaporative cooling system integrated directly beneath the PV panel using cellulose cooling pads of varying thicknesses (50 mm, 100 mm, and 150 mm), as shown in Figure 24.

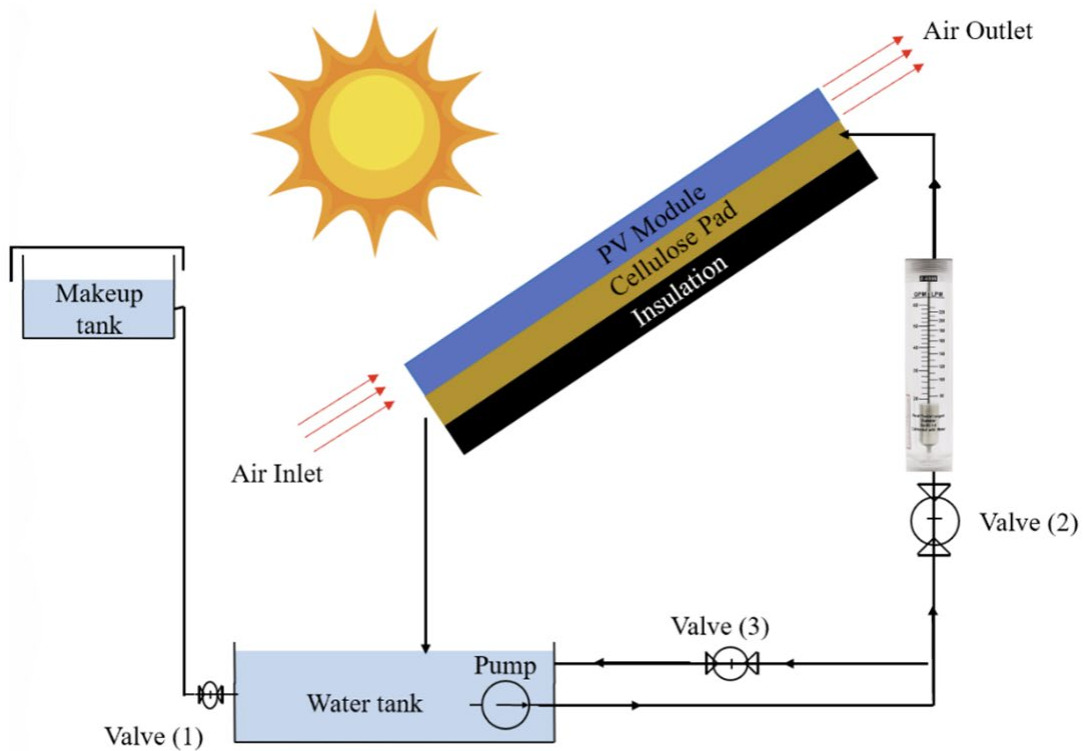


Fig. 24. Hybrid photovoltaic evaporative cooling (PV/EC) system [145].

Water flow rates of 1, 2, and 3 L/min were tested, while air velocity ranged from 2 to 3 m/s. The results showed that the PV panel's efficiency improved by 7.4%, 10.5%, and 11.2% for the 50 mm, 100 mm, and 150 mm pads, respectively. The average temperature reduction achieved was 15°C for the 50 mm pad and about 20°C for the thicker pads. Additionally, the supplied air temperature difference ranged from 5.5°C to 13.9°C, depending on the pad thickness. The results showed that the PV panel's performance, with temperature reductions of 15°C to 20°C depending on the pad thickness. The best cooling performance was achieved with the 150 mm pad at a water flow rate of 3 L/min, resulting in a supplied air dry-bulb temperature of 24.7°C and 71% relative humidity. The payback period for this cooling method was not mentioned in the report directly, however, significant gains in cooling and efficiency, it's possible that these systems could be more affordable in climates, particularly in arid regions, where conventional cooling techniques could be less effective.

Also, Ebaid et al. [146] investigated the cooling of photovoltaic (PV) panels using two types of nanofluids: TiO_2 in a water-polyethylene glycol mixture and Al_2O_3 in a water-cetyltrimethylammonium bromide mixture. The study aimed to enhance the thermal performance and efficiency of PV panels by using these nanofluids as cooling agents. The cooling system involved circulating the nanofluids through a heat exchanger attached to the

back surface of the PV panels, with flow rates varying from 500 to 5000 mL/min, as shown in Figure 25.

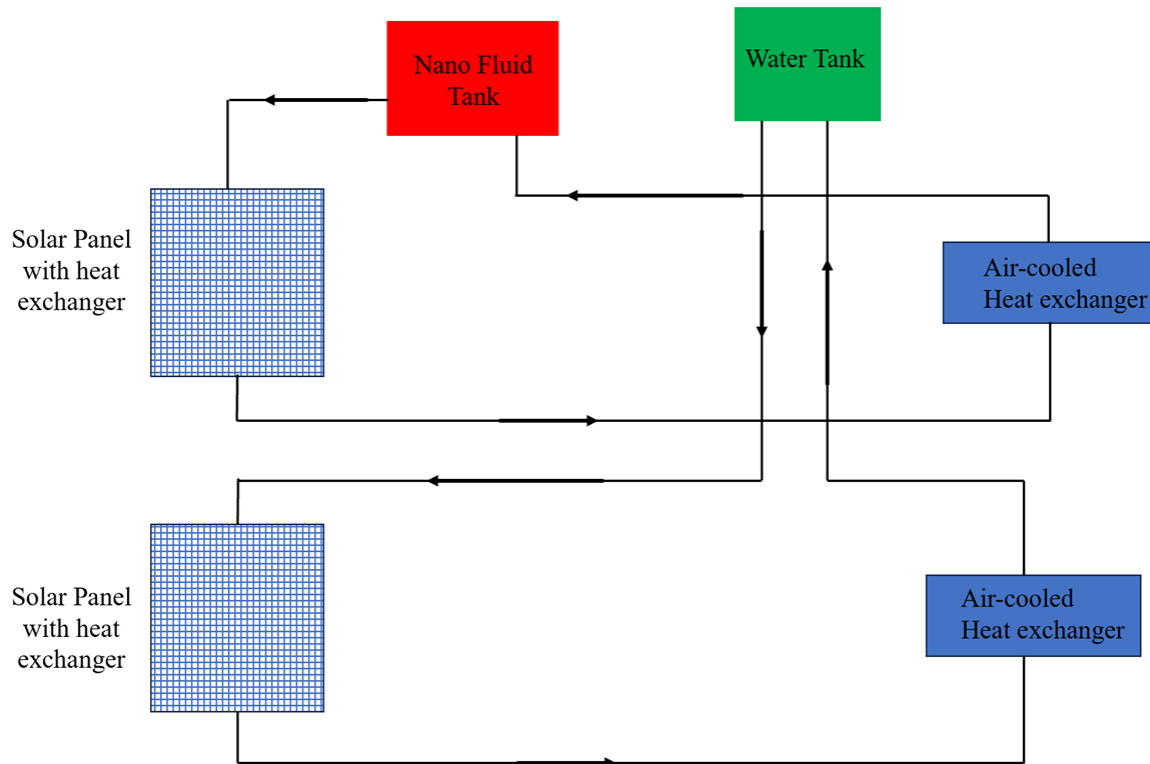


Fig. 25. Schematic of a hybrid photovoltaic system suggested by Ebaid et al. [146].

The results indicated that both nanofluids effectively reduced the PV panels' surface temperatures, with Al_2O_3 nanofluid showing better performance than TiO_2 . Specifically, the highest efficiency improvement was observed with Al_2O_3 nanofluid at 0.1 wt.% concentration, resulting in a temperature reduction of up to $18^\circ C$ compared to no cooling. This cooling effect significantly increased the electrical efficiency of the PV panels, with the maximum power output increase of 7.67% observed at a flow rate of 5000 mL/min using TiO_2 nanofluid. However, the study concentrated on the increases in thermal and electrical performance rather than providing a precise payback period for the cooling system. Inappropriate climates, these advances show possible long-term economic gains; however, a thorough financial analysis would be required to determine the payback period.

Else, Ahmad et al. [147] conducted an in-depth study on the integration and performance analysis of a large-scale hybrid system combining floating photovoltaic (FPV) panels and pumped hydro storage (PHS). The cooling method used in this study was the integration of floating PV with PHS, which allows the PV system to generate power while simultaneously

pumping water to a higher reservoir for energy storage. The results demonstrated that the optimal configuration, which included 105 MW from FPV (Block A), 80 MW from PHS, 357 MW from FPV (Block B), and the existing hydropower plant, had the lowest net present cost (NPC) and cost of energy (COE). The NPC was \$44,737,613, and the energy cost was \$40/MWh. This was significantly lower than the current hydropower plant's energy cost of \$50/MWh. The hybrid system also reduced annual CO₂ emissions by 581,830 tons and lowered the evaporation fraction of water by 17,279,400 cubic meters. The study highlighted the economic feasibility and environmental benefits of the FPV-PHS system but did not specifically mention the payback period. However, the significant reduction in energy costs and CO₂ emissions implies long-term economic benefits.

Furthermore, Sudhakar et al. [148] investigated the performance augmentation of a solar photovoltaic (PV) panel using a cooling method that integrates phase change material (PCM) and a natural water circulation cooling technique, as shown in Figure 26.

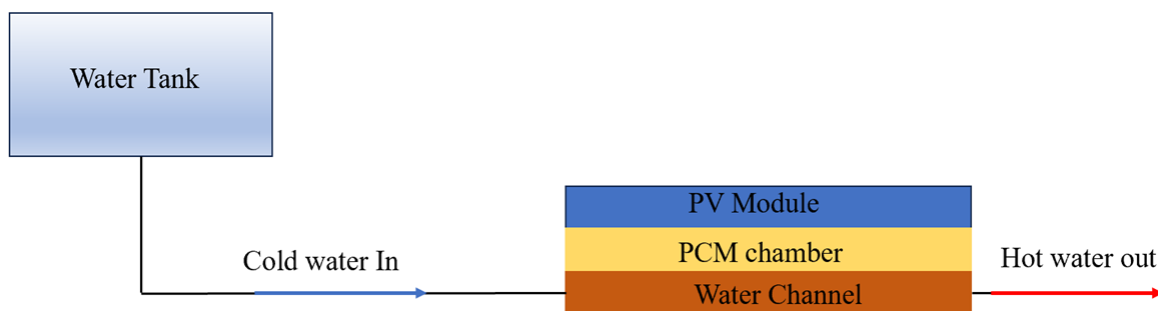


Fig. 26. Hybrid photovoltaic system suggested by Sudhakar et al. [148].

The PCM used was OM 35, a material with a phase change temperature of approximately 35°C. The study explored four different cooling scenarios based on the direction (bottom-to-top and top-to-bottom) and period (continuous and maximum allowable temperature mechanism) of water flow beneath the PCM chamber attached to the PV panel. The results indicated that the top-to-bottom continuous water supply cooling method provided the best performance, leading to significant improvements in electrical efficiency, power generation, and thermal management. Specifically, the PV-PCM panel with continuous water flow exhibited an average increase of 12.4% in electrical efficiency, 13.54% in power generation, and an average temperature reduction of 5.4°C compared to the reference PV panel without cooling. Additionally, the overall exergy output and energy efficiency of the PV-PCM system were enhanced by 26.07% and 8.08%, respectively. The improvements in efficiency and power

generation suggest potential long-term economic benefits, although further economic analysis would be required to determine the exact payback period.

In addition, Wen et al. [149] conducted an experimental and numerical study on a photovoltaic/thermal (PV/T) system that employs micro-channel heat pipes (MCHP) and thermoelectric generators (TEG) for enhanced performance. The cooling method utilized in this system involves micro-channel heat pipes that transfer heat from the PV cells to TEGs, where the heat is converted into additional electrical energy. The system also includes a water circulation mechanism to further manage the temperature. The results indicated that the system effectively improved both electrical and thermal performance. Specifically, the PV-TEG system's average electrical efficiency increased from 7.62% to 8.95%, with the TEG contributing an average electrical power of 8.33 W during a 4-hour experimental run. The water tank temperature rose from 32.89°C to 45.28°C, indicating efficient heat absorption. The system's thermal efficiency also showed a significant increase, with instantaneous thermal efficiency reaching up to 93.26% at its peak. The study did not include a specific payback period. However, the increase in electrical efficiency and thermal performance suggests potential long-term economic benefits, though further economic analysis would be required to determine the exact payback period.

Also, Torbatinezhad et al. [150] conducted a performance evaluation of a high-concentration photovoltaic/thermal (HCPV/T) system using a jet impingement and mini-channel cooling scheme. The cooling method employed involves a jet impingement coupled with a mini-channel heat sink enhanced with pin fins at various angles (0, 15, 25, 30, and 40 degrees) to improve heat transfer and maintain the PV cell's surface temperature. The study examined the effects of different mass flow rates (ranging from 0.05 to 0.15 kg/s) and concentration ratios (275, 350, 450, and 650) on the system's performance. The results showed that increasing the pin fins' angle from 0 to 40 degrees reduced the surface temperature of the solar cells, improving electrical efficiency to approximately 28.95%. The study found that the highest electrical and thermal efficiencies were around 29% and 80%, respectively, at a mass flow rate of 0.15 kg/s. The system's maximum exergy reached 2,760.59 W for the case with 40-degree pin fins. Thermal resistance also decreased with higher fin angles, contributing to improved performance.

Else, Zhang et al. [151] conducted a study on the performance prediction of a novel dual-mode heat pump system integrating a hybrid photovoltaic (PV) module with a micro-channel heat

pipe and fin heat exchanger. The cooling method involved the use of a micro-channel heat pipe (MCHP) that efficiently transported heat away from the PV cells, combined with a fin heat exchanger for enhanced heat dissipation. The system operated in two modes: cooling in summer (CIS) and heating in winter (HIW). The results demonstrated that, In the CIS mode, the system provided an average cooling capacity of 1993 W, with an average electrical output of 127.89 W. The PV temperature was maintained at around 22.73°C, and the system achieved an average COPPV of 4.72. The electrical efficiency of the PV cells averaged 17.44%. In the HIW mode, the system delivered an average heating capacity of 1756.66 W and generated 148.36 W of electricity, with a mean PV temperature of 275.69 K. The system's COPPV in this mode was 5.77.

Abdollahi et al. [152] investigated the potential of a passive cooling system for photovoltaic (PV) modules using natural water circulation coupled with a phase change material (PCM) enhanced by Boehmite nanoparticles see Figure 27.

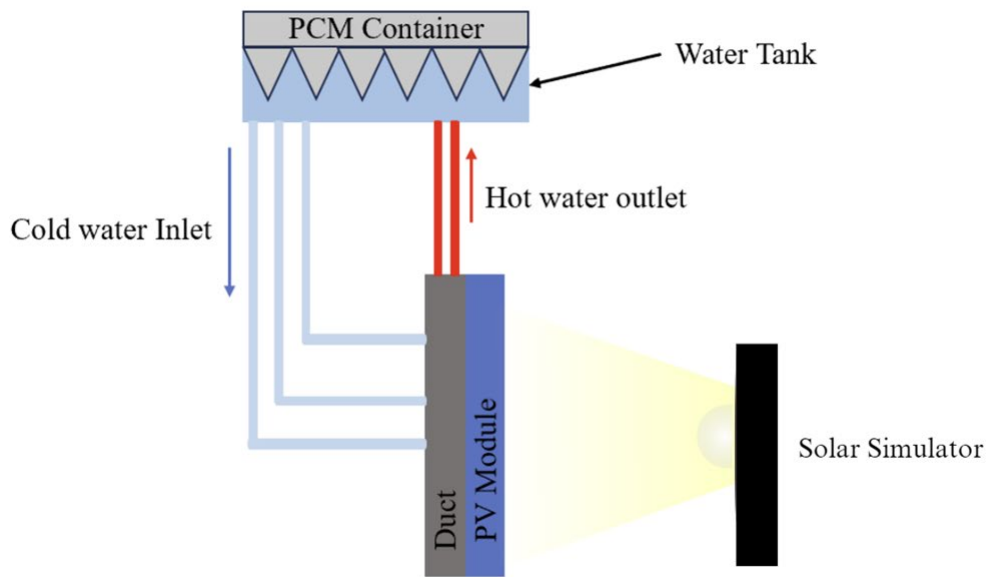


Fig. 27. Hybrid photovoltaic cooling method used by Abdollahi et al. [152].

The cooling method relied on the natural buoyant flow of water in a duct behind the PV panel, which was cooled using a PCM-based system. The PCM used was a mixture of 82 wt% coconut oil and 18 wt% sunflower oil, with Boehmite nanoparticles added to enhance thermal conductivity. The results demonstrated significant improvements in both electrical and thermal performance. The cooling system reduced the PV panel's temperature by 20.8°C, 22.6°C, and 25°C at radiation intensities of 410 W/m², 530 W/m², and 690 W/m², respectively. This led to

an increase in the panel's maximum power output by 21.19%, 26.88%, and 29.24% at the same radiation intensities when using the composite oil as PCM. When Boehmite nanoparticles were added, the power output increased further to 44.74%, 46.63%, and 48.23% under the same conditions.

Bevilacqua et al. [153] studied the seasonal performance of photovoltaic (PV) cooling systems using different methods, including spray cooling and forced convection, on the back surface of polycrystalline silicon modules. The experimental setup was deployed on the roof of the University of Calabria, Italy, and analyzed over eight months, covering various meteorological conditions. The results indicated that the spray cooling system (PV3) was the most effective, achieving a monthly energy production increase of up to 8.6% in June, with an average total energy increment of 6.1% over the analyzed period. The second spray cooling system (PV4), which included a thin metallic plate for enhanced heat distribution, showed a slightly lower performance, with a maximum energy increase of 6.7% and an average increment of 4.3%. The forced ventilation system (PV5) was the least effective, with a negligible overall energy increase of 0.04% and even a decrease in energy production in some months. The study highlighted that the spray cooling systems effectively reduced the module's operating temperature, leading to higher electrical efficiency and power generation. However, the forced ventilation system was less effective and even counterproductive due to the additional energy consumption by the fan, particularly during sunny summer months. The research did not include a specific payback period but emphasized that the simplicity and low installation costs of the spray cooling systems make them a viable option for enhancing PV performance, particularly in installations with feed-in tariffs where additional energy production can provide significant economic benefits. The total water consumption for the PV3 spray cooling system was 2.78 m³ over the analyzed period.

Nasrin et al. [154] conducted an experimental and numerical study on the performance of a photovoltaic thermal (PVT) system using a water/MWCNT (multi-walled carbon nanotube) nanofluid-based cooling system. The cooling method involved circulating the water/MWCNT nanofluid through a thermal collector attached to the back of the PV module, as shown in the cross-sectional view illustrated in Figure 28.

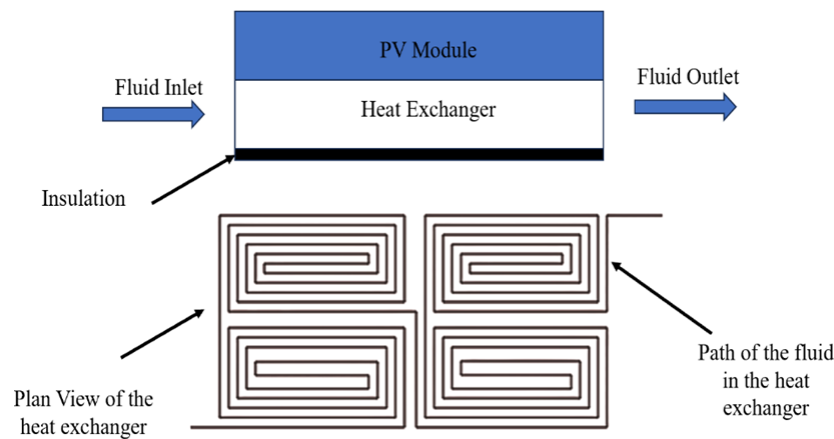


Fig. 28. Schematic of a Cross-sectional view of the PVT system used by Nasrin et al. [154].

The system aimed to improve both electrical and thermal performance under varying irradiation levels and weight fractions of MWCNT. The results showed that using the water/MWCNT nanofluid as a cooling medium significantly enhanced the system's performance. Electrical efficiency improved by approximately 9.2% compared to a system using only water as a coolant. The highest overall efficiency achieved was 87.65%, with a thermal efficiency of 75.69% and an electrical efficiency of 11.96% at 1000 W/m² irradiation and 1% weight fraction of MWCNT. The study demonstrated that the use of nanofluid led to a thermal energy gain of approximately 113.14 W for every 100 W/m² increase in irradiation.

The hybrid cooling systems mentioned above represent new and innovative approaches that significantly enhance thermal efficiency, electrical efficiency, and power generation compared to systems utilizing a single cooling technique. Researchers should intensify their efforts to explore more advanced techniques, focusing on improving solar cell efficiencies. However, it's equally important for researchers to investigate the payback period and environmental impact of these methods. This comprehensive approach will not only advance the field but also guide the selection of the most effective and sustainable techniques for implementation. Among the hybrid cooling systems discussed, the system developed by Wen et al. demonstrated the most significant improvement in thermal efficiency, achieving a peak instantaneous thermal efficiency of 93.26%. Meanwhile, the system by Torbatinezhad et al. excelled in enhancing electrical efficiency. However, the method proposed by Elavarasan et al. stands out as particularly promising, offering a balanced combination of electrical and thermal efficiencies, a favorable payback period, and the added advantage of easy installation. This makes it a compelling option for practical implementation.

The synergistic processes of hybrid cooling systems reside in how several strategies mitigate each other's shortcomings. PCM layers can mitigate temperature increases at peak irradiance, whereas nanofluid circulation improves dynamic heat dissipation, leading to more stable panel temperatures. Likewise, the combination of spray cooling with geothermal exchangers facilitates the continuous recycling of water at reduced temperatures, while the integration of thermoelectric generators with microchannel heat pipes permits concurrent cooling and supplementary power generation. These synergies are essential for realising efficiency improvements that exceed the aggregate of separate strategies.

To enhance system performance, various optimisation strategies are identified in the literature: regulating fluid flow rates to equilibrate pumping power and heat dissipation, customising PCM thickness and positioning for diverse climates, engineering microchannel geometries to reduce pressure losses, and choosing nanofluid concentrations that maximise conductivity while preventing sedimentation or excessive viscosity. Moreover, adaptive control systems that modulate water spraying or flow rates based on solar irradiation can markedly enhance efficiency and sustainability in water usage.

Nonetheless, although hybrid cooling systems exhibit significant efficiency enhancements, their practical viability and cost-effectiveness continue to pose challenges. Intricate designs typically necessitate greater initial capital, elevated maintenance demands, and concerns regarding longevity, including nanoparticle stability and phase change material leaking over time. Water accessibility and usage are essential factors, especially in arid areas. Furthermore, the payback period may fluctuate significantly according to regional electricity rates, meteorological factors, and system size. Future research for large-scale implementation must enhance technical performance while also considering long-term economic feasibility, lifetime costs, and environmental trade-offs to facilitate the transition of these systems from experimental frameworks to commercially viable technologies.

7. Discussion

According to the literature, a wide range of cooling techniques have been employed to reduce the temperature of photovoltaic (PV) panels, thereby enhancing their efficiency. These methods aim to mitigate the adverse effects of heat accumulation, which can significantly diminish the performance of PV systems. By lowering the operating temperature, these cooling strategies help optimize energy output and prolong the lifespan of the panels, making them more effective and sustainable in various environmental conditions.

Among the various cooling techniques examined in this paper, special emphasis is placed on water cooling, as it has been demonstrated to outperform other methods in significantly enhancing the efficiency of photovoltaic (PV) panels, as shown in the bar graph of Figure 29 that represents the median efficiency of each set of values discussed in the review section for various water-cooling methods. These cooling techniques can improve electrical output efficiency, with gains ranging from 8.08% to 49.6%.

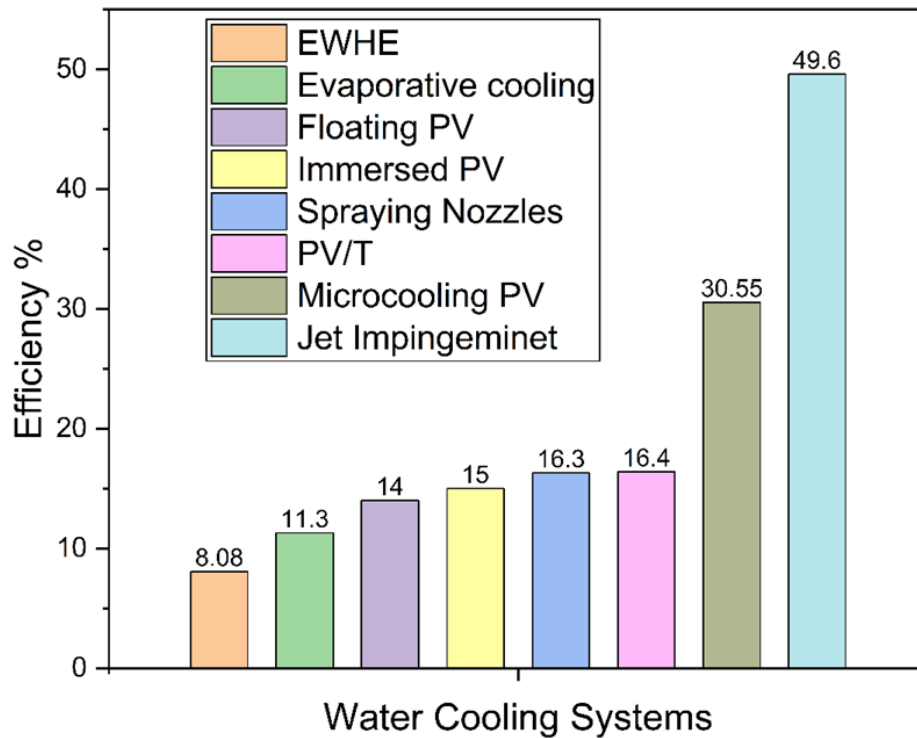


Fig. 29. The mean efficiency of different cooling techniques.

However, the implementation of water-based systems incurs higher costs due to the need for additional components such as pumps, pipes, and fittings. Despite these costs, water cooling is particularly advantageous in regions prone to dust or sand accumulation. In such environments, it not only helps maintain higher efficiency by cooling the panels but also serves to clean the surface of the PV modules, removing dust that would otherwise obstruct sunlight and reducing the amount of irradiation absorbed by the panels. This dual benefit makes water cooling an especially effective solution in dusty or sandy locations.

On the other hand, the continuous use of water may not be feasible in arid regions due to water scarcity. Additionally, improper system design can lead to leaks, potentially damaging electrical components and accelerating corrosion over time. Furthermore, most water-cooling techniques require additional electrical power to operate pumps, which can offset some of the energy gains achieved through cooling.

Additionally, hybrid cooling systems that incorporate water have proven to be highly effective in enhancing PV panel efficiency. These systems combine the advantages of water cooling with other techniques to achieve superior thermal regulation. However, they tend to come with higher costs and increased complexity in installation due to the integration of multiple cooling mechanisms and the need for additional infrastructure. Despite these challenges, the performance gains from hybrid cooling systems make them a promising option for improving PV efficiency in demanding environments.

This review explores various water-cooling techniques for photovoltaic panels and their impact on electrical efficiency enhancement. The primary objective is to identify promising methods that merit further research. Water-cooling approaches, including water immersion, floating photovoltaic panels, spray nozzles, evaporative cooling, thermal photovoltaic panels, earth-water heat exchangers, micro-cooling channels, and jet impingement, have demonstrated efficiency improvements ranging from 8.08% to 49.6%.

Furthermore, hybrid water-cooling methods, which integrate multiple cooling techniques, offer even more significant enhancements in both electrical and thermal efficiencies. This review paper also examines the advantages and disadvantages of different water-cooling strategies. Table 10 provides a comprehensive summary of various water-cooling techniques for photovoltaic panels, highlighting their respective advantages and disadvantages, providing researchers with a comprehensive understanding of how to refine and optimize these cooling solutions. This analysis enables researchers to identify key limitations within these systems, paving the way for future improvements in design and efficiency.

Table 10: Advantages and disadvantages of water-cooling techniques,

Water Cooling Techniques	Advantages	Disadvantages
Immersed PV	<ul style="list-style-type: none"> • Dust and Dirt removal • Low cost • Provides a uniform cooling across the entire surface of the PV 	<ul style="list-style-type: none"> • Performance depends on the depth of the immersion • High water consumption • Can cause corrosion for PV panel
Floating PV	<ul style="list-style-type: none"> • Reduce the usage of land • Can be combined with hydropower dams for integrated energy solutions • Good efficiencies improvement 	<ul style="list-style-type: none"> • Need large areas to be installed • High-cost installation • Stability of the structure in bad weather conditions is challenging
Spray Nozzles	<ul style="list-style-type: none"> • Low water consumption • Good efficiencies improvement 	<ul style="list-style-type: none"> • High installation cost • Requires more electrical power

	<ul style="list-style-type: none"> Automated and adjustable 	<ul style="list-style-type: none"> Sensitive to wind conditions
EWHE	<ul style="list-style-type: none"> No risk of short circuits Low maintenance cost No water evaporation 	<ul style="list-style-type: none"> Low improvement efficiency High installation cost Need sufficient land areas
PVT	<ul style="list-style-type: none"> Good efficiencies improvement Less installation space The collected thermal energy can be used for domestic heating applications 	<ul style="list-style-type: none"> Potential of overheating Complicated installation The cooling process decreases in hot climates
Micro-cooling	<ul style="list-style-type: none"> High-efficiency improvement Optimizing performance Reduce the risk of electrical short circuits 	<ul style="list-style-type: none"> High installation cost Repairing process Consumes more electrical power
Jet impingement	<ul style="list-style-type: none"> High efficiency improvement No additional installation space Low water consumption 	<ul style="list-style-type: none"> Noisy Requires high electric energy Risk of damage in case of high-water velocity

The results indicate considerable potential for water-based and hybrid cooling methods; nonetheless, numerous problems persist that must be meticulously resolved prior to widespread implementation. Nanofluid cooling provides superior heat transfer rates owing to improved thermal conductivity; yet challenges such as particle agglomeration, sedimentation, and long-term stability may restrict its practical reliability. Phase change materials (PCMs) are proficient in thermal energy storage and release; nonetheless, they frequently exhibit limited thermal conductivity, leakage issues, and increased system weight, complicating their integration with photovoltaic modules. Immersion cooling, while typically categorised as passive, may provide problems associated with fluid deterioration, material compatibility, and maintenance demands during prolonged operational durations. These technological obstacles underscore the necessity for more material innovations, standardised evaluations, and durability assessments.

The trade-offs are equally significant from both economic and environmental viewpoints. Systems utilising active water circulation, micro-channels, or jet impingement attain excellent cooling efficiency; yet they necessitate pumps and external energy input, thus diminishing the overall energy benefits. In arid climates, the sustainability of water utilisation is a paramount issue, especially for spray or immersion techniques. Conversely, hybrid systems that use TEGs (thermoelectric generators) or PCMs with nanofluids demonstrate enhanced performance and

environmental advantages; nevertheless, their substantial initial costs, installation difficulty, and ambiguous long-term return on investment hinder broad implementation. Mitigating these problems via cost reduction, modular system design, and enhanced resource management will be crucial for guaranteeing that the advantages of these new cooling approaches surpass their drawbacks.

This study has meticulously evaluated thermal reduction and electrical efficiency, along with other essential criteria that influence the practical viability of water-based cooling systems. Emphasis has been placed on the energy demands of active systems, the intricacy of installation for various designs, and their corresponding expenses. Active cooling techniques, including water spraying, jet impingement, and microchannel circulation, typically provide enhanced temperature reductions and efficiency improvements; nevertheless, they require additional energy for pumping or fluid circulation. This parasitic energy consumption mitigates a portion of the total electrical gain, underscoring the necessity of assessing net efficiency rather than solely electrical output.

Additionally, the intricacy of installation and scalability offer additional aspect for evaluation. Passive approaches, such as immersion cooling, floating photovoltaic systems, and evaporative systems, typically necessitate less mechanical components, resulting in quicker installation and maintenance, which renders them appealing for small-scale or resource-limited environments. In contrast, microchannel systems and hybrid PVT arrangements, although highly efficient, need sophisticated design, specialised materials, and meticulous integration with existing PV infrastructure. These constraints frequently elevate capital investment and maintenance demands, which must be evaluated against their performance benefits.

This comprehensive comparison contextualises laboratory data within practical limits and provides essential assistance for decision-makers, researchers, and industry stakeholders. It emphasises that the optimal cooling method is contingent upon context, weighing enhancements in efficiency against operational expenses, system longevity, and ease of deployment. This comprehensive approach guarantees that the evaluation functions as both a scientific reference and a practical guide for the advancement of sustainable photovoltaic cooling technology.

Innovative cooling methods, particularly nanofluid-based systems, demonstrate significant potential for improving the thermal and electrical efficiency of solar panels. Nanofluids, such as those containing Al_2O_3 , ZnO , CuO , and carbon-based nanoparticles, have markedly enhanced thermal conductivity and heat transfer characteristics relative to standard water. These

characteristics render them formidable contenders for sophisticated cooling applications. The scaling of nanofluid systems encounters numerous problems, such as the long-term stability of nanoparticle suspensions, agglomeration, elevated viscosity at greater concentrations, and the possible environmental consequences of nanoparticle discharge. Subsequent study should concentrate on long-term durability evaluations in outdoor environments, environmental safety analyses, and the establishment of standardised nanoparticle concentrations that optimise performance while considering cost and sustainability.

A viable approach is hybrid evaporative–radiative cooling, which integrates two complimentary processes: evaporative cooling during peak sunlight and radiative sky cooling at night. This dual strategy may provide uninterrupted 24-hour cooling, markedly lowering PV surface temperatures and enhancing performance in arid and semi-arid environments. However, the practical implementation of such systems poses significant obstacles. This encompasses optimising water usage in arid places, creating resilient and spectrally selective coatings for radiative cooling, and engineering small systems suitable for retrofitting existing rooftop and utility-scale installations. Resolving these difficulties necessitates both experimental validation and multi-objective optimisation analyses that balance cooling effectiveness with water conservation, durability, and cost.

Looking ahead, the future of PV cooling research should move toward multi-dimensional assessments that combine technical, economic, and environmental perspectives. Comparative analyses across cooling strategies must not only report thermal and electrical performance but also quantify costs, water usage, and CO₂ reduction potential. In addition, the integration of smart monitoring and control systems leveraging IoT-based sensors and AI-driven optimization can help dynamically adjust cooling operation to local weather and irradiance conditions, thereby improving system efficiency while reducing unnecessary resource use. Finally, long-term field trials across diverse climatic zones remain essential to validate laboratory results and address maintenance, fouling, and degradation challenges. By advancing in these directions, the research community can accelerate the transition of emerging cooling technologies from experimental concepts to commercially viable, sustainable solutions.

8. Challenges and limitations

Considering the significant advancements made in water-based cooling systems for photovoltaic (PV) modules, various technological, economic, and practical difficulties persist, hindering their widespread use.

Starting by the Technological constraints; Tests are performed in controlled laboratory settings or with fixing some constraints so that it fails to accurately reflect actual outdoor circumstances characterised by variable sun irradiance, wind speed, humidity, and dust accumulation. The long-term resilience of materials subjected to water specifically the corrosion of metallic conduits, biofouling, and scaling remains insufficiently studied. The absence of standardised measurement methodologies and efficiency standards obstructs accurate comparisons among systems (immersion, floating, spray, PVT, micro-channel, and jet-impingement).

In addition to the technical limits, economic and operational constraints significantly influence the feasibility of water-based cooling systems. While active systems (such as PVT and jet-impingement) provide enhanced cooling performance, their parasitic power consumption and pumping expenses sometimes negate the electrical efficiency benefits, hence generating significant concerns about their cost-effectiveness and energy payback period. Conversely, passive systems, although often more energy efficient and easier to manage, exhibit restricted controllability and diminished heat-transfer efficacy in low-wind or stagnant air scenarios. Moreover, the availability, utilisation, and recycling of water provide significant issues, especially in arid and semi-arid areas, where the expansion of solar PV deployment is accelerating despite limited water supplies.

Although the incorporation of cooling subsystems into extensive solar (PV) farms or building-integrated photovoltaic installations adds considerable design complexity and maintenance requirements, potentially impacting system dependability and long-term performance. These integrated systems necessitate meticulous coordination among electrical, thermal, hydraulic, and structural components to guarantee safe and efficient functioning. The interrelationship of hydraulic design, thermal performance, and structural stability especially in floating photovoltaic applications continues to pose a significant engineering problem. Inadequate hydraulic setup might result in unequal cooling distribution, mechanical stress, or water leaks, whilst insufficient structural design may jeopardise buoyancy and safety.

To overcome these issues, systematic optimisation using multi objective modelling and simulation is crucial, balancing energy efficiency, cooling uniformity, cost, and mechanical integrity. These methods can facilitate the identification of appropriate trade-offs between

thermal improvement and system durability, hence enabling more scalable and sustainable designs. Furthermore, the incorporation of intelligent monitoring systems, IoT sensors, artificial intelligence, and predictive maintenance algorithms such as machine learning can enhance reliability by facilitating real time management and early failure detection elevating water-based cooling from a mere technical accessory to a fully integrated, intelligent subsystem within next-generation photovoltaic installations.

9. Observations and Implications

This thorough research illustrates that water-based cooling solutions both passive and active provide the most reliable and effective thermal management strategy for solar systems in comparison to air or PCM-only methods. Principal observations encompass the subsequent points:

- 1. Performance enhancement:** Water-based cooling can decrease photovoltaic temperatures by up to 46%, enhance electrical efficiency by 6–38%, and increase power output by approximately 47%, contingent upon design and flow configuration.
- 2. System selection trade-off:** Active approaches (spray, jet impingement, PVT) offer enhanced cooling intensity but elevate system complexity and operational costs, whilst passive systems (evaporative, immersion, floating PV) maintain simplicity and sustainability for decentralised applications.
- 3. Environmental significance:** Effective cooling mitigates thermal stress and material deterioration, prolonging the lifespan of photovoltaic modules and thereby reducing the overall carbon footprint of solar electricity production.
- 4. Economic implications:** When optimised for flow rate, pump power, and water reuse, water-based cooling systems can attain advantageous energy payback periods in comparison to dry or air-based systems, especially in areas with significant solar insolation.
- 5. Urban and industrial integration:** Integrating photovoltaic cooling with water networks, geothermal loops, or wastewater treatment facilities offers further prospects for circular-economy applications and enhanced resource utilisation. This study underscores that water-based cooling serves not only as a performance enhancer but also as a strategic approach to sustainable photovoltaic deployment. The incorporation of new materials, intelligent control systems, and hybrid energy solutions

can propel the advancement of high-efficiency, low-emission solar technologies in residential, industrial, and utility-scale domains.

10. Conclusions

This study provides a comprehensive review of advanced cooling techniques for photovoltaic panels, with a special emphasis on water-based methods and their hybrid integrations. A novel classification framework was introduced to systematically analyze and compare these approaches. The conclusion encapsulates the important findings while addressing the significant problems, prospects, and broader implications. The review indicates that water-based cooling techniques can significantly lower PV module temperatures (up to 46%) and enhance efficiency (6–38%), however their implementation faces challenges concerning cost, material durability, and water accessibility. Emerging hybrid approaches exhibit considerable potential, contingent upon further research resolving these limitations.

Furthermore, the discourse emphasises that technological innovation by itself is inadequate; strong policy interventions and sustainability factors are crucial for converting laboratory breakthroughs into practical energy transformations. By synchronising research initiatives with regulatory frameworks and resource management methods, water-based PV cooling can transition from experimental applications to large-scale, significant solutions that enhance energy efficiency and climate resilience.

11. Future recommendations

- Water-based hybrid cooling methods should receive special focus due to their superior efficiency compared to other cooling techniques.
- Researchers should prioritize the economic and environmental analysis of water hybrid cooling systems. Given their high efficiency, it is crucial to assess their long-term cost-effectiveness and environmental impact. A comprehensive evaluation of these factors will provide valuable insights into the feasibility and sustainability of water hybrid systems, guiding future innovations and applications in PV cooling technology.
- Researchers should also focus on evaluating the payback period of water hybrid cooling systems. Understanding the timeframe in which the initial investment is recovered is essential for assessing the economic viability of these systems.

- Researchers should also move beyond purely thermal and electrical efficiency to include multi-factor quantitative analyses. Such frameworks would allow a more realistic evaluation of cooling methods and guide stakeholders in selecting the most feasible technology for specific applications.
- To strengthen decision-making, future studies should present concrete numerical benchmarks of cooling strategies across multiple axes, including cost per unit of energy gained, Liters of water consumed per kWh, and kilograms of CO₂ saved annually.
 - Developing **hybrid and self-regulated systems** combining water cooling with PCM, nanofluids, or thermoelectric elements to balance performance and sustainability.
 - Conducting **long-term field tests** in diverse climates to assess degradation, maintenance cycles, and lifecycle cost.
 - Investigating **smart control and IoT-based monitoring** for adaptive flow regulation and fault detection.
 - Employing **computational fluid dynamics (CFD)** and **AI-assisted optimization** to design high-efficiency micro-channels and spray geometries.
 - Exploring **closed-loop or recycled-water cooling** to ensure environmental compliance and reduce freshwater consumption.

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