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A Review Paper: Enhancement of the Efficiency of PV Systems by Evaporative and Water-Cooling Methods

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***Abstract*— The efficiency of photovoltaic systems is significantly affected by operating temperatures, which can lead to considerable energy losses, particularly in high-irradiance regions. Despite advancements in photovoltaic technology, excessive heat buildup remains a major challenge, reducing power output and system longevity. Various cooling techniques have been explored to mitigate thermal effects; however, there is still a gap in understanding the comparative effectiveness of different methods, particularly in extreme environmental conditions. This paper aims to address this gap by evaluating and recommending two promising cooling strategies: evaporative cooling and water cooling. Evaporative cooling leverages the natural heat absorption of water evaporation to reduce panel temperatures efficiently, making it particularly suitable for hot and arid climates. Water cooling, on the other hand, directly dissipates heat through fluid circulation, offering higher efficiency gains and potential integration with hybrid photovoltaic-thermal systems. By analyzing the benefits and practical implementation of these techniques, this study provides valuable insights into optimizing photovoltaic system performance and extending operational lifespan. Future research should focus on refining these methods for large-scale applications while assessing their economic and environmental viability.**

Keywords*— *Review, PV cooling, evaporative cooling, water cooling, Efficiency.

1. Introduction

The world faces a growing demand for clean and sustainable energy, driven by concerns over climate change, environmental degradation, and the depletion of non-renewable resources like fossil fuels. In response to these challenges, renewable energy sources such as solar, wind, and hydropower are increasingly seen as essential components of the future global energy mix. Solar power has gained immense traction due to its availability, technological advancements, and the potential to provide decentralized energy solutions. Among the various solar energy technologies, photovoltaic (PV) systems play a crucial role in converting sunlight directly into electricity.

PV panels are designed to capture solar radiation and convert it into electrical energy through the photovoltaic effect. Despite their potential, the efficiency of PV panels is significantly affected by environmental factors, particularly temperature[1]. High temperatures reduce the efficiency of PV panels, leading to lower energy output. In regions with high solar irradiance, such as deserts or tropical climates, PV panel temperatures can exceed optimal operating conditions, causing substantial losses in efficiency[2], [3].

To mitigate this problem, cooling techniques for PV panels have become a subject of extensive research. Effective cooling strategies can help maintain the temperature of PV panels within the desired range, thereby improving their efficiency and extending their lifespan. This paper provides a careful examination of two promising cooling techniques (evaporative cooling and water cooling) for photovoltaic systems. While previous studies have explored these methods individually, this work seeks to compare their performance and practical implications across different climatic conditions. The aim is to offer a balanced perspective that highlights the potential benefits and limitations of each technique, thus filling a small but important gap in the current understanding of photovoltaic thermal management. Ultimately, this review is intended to support further research and innovation in optimizing photovoltaic efficiency and system longevity.

Following this introduction, Section 2 presents an overview of the fundamentals of photovoltaic panel operation and explains how various thermal conditions impact system performance. Section 3 details water-cooling techniques, while Section 4 examines humidified air-cooling methods. Section 5 offers a comparative analysis of the two cooling approaches, highlighting their respective advantages and limitations. Section 6 explores advanced cooling technologies, including phase change materials, nanofluids, and hybrid systems. Finally, Section 7 concludes the paper by summarizing the key findings and suggesting directions for future research, and Section 8 lists the references.

2. Fundamentals of PV Panel Operation and Thermal Management

Before delving into specific cooling techniques, it is essential to understand how PV panels operate and why temperature management is crucial to their performance.

2.1. Physics of Photovoltaic Cells

Photovoltaic cells, the core components of PV panels, are semiconductor devices that convert solar energy into electricity through the photovoltaic effect. When sunlight strikes the surface of a PV cell, photons are absorbed by the semiconductor material (typically silicon), exciting electrons and causing them to flow through an external circuit, generating electric current. The amount of generated electricity depends on several factors, including the intensity of sunlight, the angle of incidence, and the temperature of the PV cells [4].

2.2. Parameters Affecting PV System Efficiency:

- **Solar Irradiance** – Higher irradiance increases power output but also raises temperature, which can reduce efficiency[5].
- **Temperature** – Increased cell temperature leads to efficiency loss due to reduced open-circuit voltage.
- **Dust and Soiling** – Accumulation on the PV surface reduces the amount of sunlight reaching the cells[6].
- **Shading Effects** – Partial shading significantly reduces power generation[7].
- **Humidity and Wind Speed** – Wind helps cool PV panels, while high humidity may lead to condensation and material degradation[8].
- **Angle of Incidence & Tilt Angle** – Affects how much solar radiation is captured[9].
- **Type of PV Material** – Monocrystalline vs. polycrystalline vs. thin-film cells have different temperature coefficients[10].

2.3. Impact of Temperature on PV Efficiency

The efficiency of PV panels is inversely related to their operating temperature. As the temperature of the PV cells increases, the bandgap energy of the semiconductor material decreases, reducing the open-circuit voltage and, consequently, the overall efficiency of the PV system. For most commercial silicon-based PV panels, the efficiency drops by approximately 0.4% to 0.5% for every degree Celsius increase in temperature[11]. In regions with high solar irradiance, PV panels can reach temperatures exceeding 60°C, resulting in efficiency losses of up to 20% or more [11],[12].

2.4. Thermal Management in PV Systems

Effective thermal management is critical for maintaining the performance of PV panels. Without adequate cooling, high temperatures can not only reduce the efficiency but also accelerate the degradation of the PV cells, shortening the lifespan of the system. Cooling techniques are employed to dissipate excess heat, either through passive methods (such as enhanced air flow or heat-dissipating materials) or active methods (such as water or air cooling).

Active cooling methods, which involve external interventions to lower the temperature of the PV panels, have been shown to be more effective than passive methods in hot climates. Among the various active cooling techniques, water cooling and humidified air-cooling have gained attention due to their potential to significantly reduce PV temperatures and improve system performance.

3. Water Cooling of PV Panels

Water cooling is one of the most widely studied and effective techniques for reducing the temperature of photovoltaic (PV) panels. The principle behind water cooling is simple: water has a high specific heat capacity, meaning it can absorb significant amounts of heat with minimal temperature increase. By circulating water over or beneath the surface of PV panels, excess heat is transferred from the panels to the water, thereby reducing their operating temperature. Numerous designs and configurations of water-cooling systems have been developed, ranging from simple spraying mechanisms to sophisticated water circulation systems integrated with heat exchangers.

3.1. Mechanisms of Water Cooling:

The cooling mechanism in water-cooled PV systems is based on heat transfer between the panel and the water. When water encounters the heated surface of the PV panel, it absorbs the heat through both convection and conduction processes. In systems where water is sprayed over the surface, additional cooling occurs through evaporation. Evaporative cooling enhances the overall heat dissipation process by utilizing the latent heat of vaporization. The cooled water can either be discarded or recycled in a closed-loop system, where it is cooled further before being reused.

Water cooling systems can reduce PV panel temperatures by as much as 15–20°C [13], significantly improving their performance, particularly in hot and sunny climates. This cooling effect can lead to a relative increase in power output of around 10–15% [14], depending on the initial temperature and the design of the cooling system.

3.2. Types of Water-Cooling Systems

There are several designs for water cooling systems, each with varying levels of complexity, efficiency, and water consumption. Below are the main types of water-cooling systems:

3.2.1. Surface Water-Cooling (Spraying or Immersion)

- Direct Spraying: In this method, water is sprayed onto the front or back surface of the PV panels as in figure 1. This is a simple and cost-effective way to cool the panels.

Sprinklers or nozzles are typically used to distribute water uniformly over the panel surface.

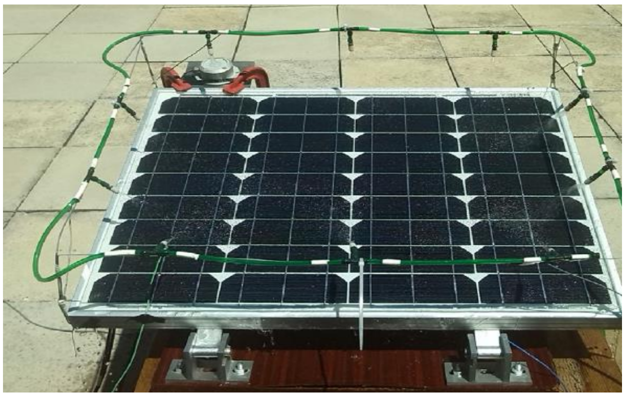

FIGURE 1. PV PANEL WITH SPECIFIC WATER NOZZLE SYSTEM S. [13]

- Immersion Cooling: This method involves partially or fully immersing the PV panels in water. Immersion cooling is effective because the water directly absorbs heat from the panels, providing consistent cooling across the entire surface.
- Advantages: Both spraying and immersion techniques can significantly reduce temperatures at relatively low cost. These methods also provide the benefit of cleaning the panel surface, improving efficiency by reducing dust and dirt accumulation.
- Limitations: Direct water contact may accelerate the degradation of PV materials due to corrosion or soiling. Regular maintenance and careful material selection are required to prevent damage.

3.2.2. Water Circulation Beneath the Panels

- Design: In this method, water is circulated through tubes or channels placed beneath the PV panels as in figure 2. The water absorbs heat from the underside of the panel, cooling the entire structure without directly wetting the PV cells. This approach prevents soiling of the panel surface and reduces the risk of corrosion.

FIGURE 2. WATER COOLING COPPER PIPE [15].

- Cooling Process: Water flows through the channels, absorbs heat from the bottom of the panel, and exits to be cooled and recirculated. This can be achieved using natural convection or a pump-driven system for continuous circulation.
- Advantages: This method avoids direct contact between water and sensitive PV surfaces, thereby extending the life of the panels. It also allows for easier integration with existing panel designs.
- Limitations: The efficiency of heat transfer is lower compared to direct spraying or immersion. In addition, the use of pumps and pipes adds complexity and cost to the system.

3.2.3. Hybrid PV/Thermal (PV/T) Systems

- Design: In hybrid PV/T systems, a thermal absorber is attached to the backside of the PV panels, capturing the heat that would otherwise raise the temperature of the panels as in figure 3. Water or another fluid is circulated through the absorber to collect the thermal energy, cooling the panels while generating usable thermal energy.

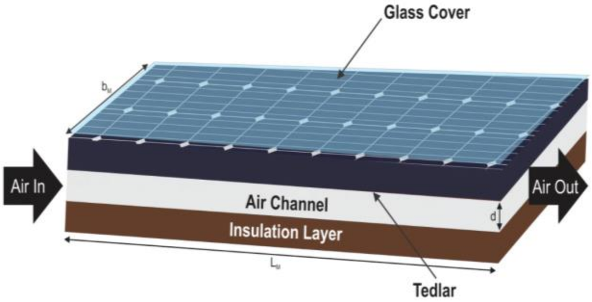

FIGURE 3. PHOTOVOLTAIC-THERMAL (PV/T) SYSTEM DESIGN [16].

- Dual Use: The captured heat can be used for applications such as space heating, water heating, or industrial processes, making these systems highly efficient in overall energy output (both electrical and thermal).
- Advantages: Hybrid systems enhance the total energy yield of the system by converting waste heat into useful thermal energy. This improves the economic viability of PV systems, particularly in large-scale installations.
- Limitations: Hybrid systems are more complex and costly to install and maintain. Additionally, the design needs to balance the electrical efficiency of the PV panels with the thermal efficiency of the heat absorber, which can sometimes result in trade-offs.

3.3. Advantages of Water Cooling

- Enhanced Efficiency: Water cooling can significantly reduce the operating temperature of PV panels, leading to improved electrical efficiency. Research has demonstrated efficiency gains of up to 15% in regions with high ambient temperatures.

- Extended Lifespan: Operating at lower temperatures reduces the thermal stress on PV panels, slowing down material degradation and extending the lifespan of the system.

- Simultaneous Cleaning: Systems that involve water spraying or washing can help clean the PV panels, reducing soiling losses. Dust and debris accumulation on the panel surface can reduce efficiency by 5-10% [17], [18], making cleaning an added benefit of water cooling.

- Hybrid Energy Production: Hybrid PV/T systems can generate both electricity and thermal energy, increasing the overall energy output and enhancing the economic feasibility of PV installations [19], [20].

3.4. Limitations and Challenges

- Water Consumption: One of the primary drawbacks of water cooling is its reliance on a consistent water supply. This can be a significant issue in arid regions where water scarcity is a concern. Systems with high water consumption may not be sustainable or cost-effective in such environments.

- Corrosion and Soiling: Direct contact between water and the PV panel surface can lead to issues such as corrosion and mineral deposition (scaling) [21]. These factors can degrade the materials and reduce the efficiency of the system over time. Careful selection of water treatment methods and materials is necessary to mitigate these risks.

- Energy Use in Active Systems: Water cooling systems that rely on pumps for water circulation consume additional energy. This energy consumption can offset some of the gains achieved by cooling the panels, especially in regions where electricity is expensive or where renewable energy sources are not yet dominant.

- Installation and Maintenance Costs: Installing water cooling systems adds complexity to PV installations. Additional infrastructure such as pumps, pipes, and storage tanks are required. Moreover, these systems require regular maintenance to prevent issues like water leaks, pump failures, or scaling in the water lines.

3.5. Recent Research and Case Studies on Water Cooling

Several studies have investigated the performance of water-cooled PV systems under different environmental conditions. Research has demonstrated the effectiveness of water cooling in hot climates, particularly in regions like the Middle East, North Africa, and Southeast Asia, where high temperatures and solar irradiance are common. Some notable research findings include:

H. Bahaidarah et al. [22] evaluated the performance enhancement of a photovoltaic (PV) module using a back-surface water cooling system, particularly in hot climatic conditions where high temperatures significantly degrade PV efficiency. The cooling system involves the circulation of water across the rear surface of the PV module, which absorbs excess heat and lowers the module's operating temperature. Both experimental and analytical approaches were employed to assess the system's impact on temperature reduction, electrical efficiency, and power output. The results demonstrate that back-surface water cooling effectively reduces the PV module's temperature by 10–20°C, depending on the ambient conditions and flow rate of the cooling water. This reduction in temperature translates into a marked improvement in electrical efficiency, with gains ranging from 5% to 15% compared to uncooled modules. Additionally, the power output of the cooled PV module increases by 10–20%, as the system operates closer to its optimal temperature range.

S. Niˇzeti'c et al. [13] used a water spray cooling technique to reduce the operating temperature of the PV panel and analyzed the impact on its efficiency and power output. The methodology involved applying a fine mist of water on the surface of the PV panel and measuring the temperature reduction and corresponding performance improvements under various environmental conditions. The cooling effect of the water spray was carefully monitored to determine its impact on the electrical performance of the panel. Key results showed a significant decrease in the operating temperature of the PV panel, which led to an increase in overall efficiency. The water spray cooling reduced the temperature by up to 16°C, which resulted in a performance improvement of approximately 10.3%. This enhancement in efficiency was linked to the fact that PV panels typically lose efficiency as their operating temperature rises, and the cooling system mitigated this loss. Additionally, the study found an increase in the electrical power output of the panel due to the cooling, showing the effectiveness of the water spray as a simple and efficient cooling solution.

Bin Wan Abdullah et al. [15] investigated the application of water-cooling systems to enhance the performance of photovoltaic (PV) modules. The methodology involves circulating water across the PV module to absorb excess heat, thereby reducing the temperature of the module. This cooling mechanism helps to mitigate the temperature-induced losses in electrical efficiency that typically occur in hot climates. The experimental setup evaluates the impact of varying water flow rates and ambient temperatures on the module’s temperature, electrical efficiency, and power output. The results demonstrate that water cooling effectively lowers the temperature of the PV module by 10–20°C, depending on the cooling rate and environmental conditions. As a result, the electrical efficiency of the PV module increases by 5% to 15%, and the power output improves by 10% to 20% compared to uncooled modules. This cooling method not only enhances the efficiency of the PV system but also reduces the thermal stress on the module, potentially extending its operational life. The study concludes that water cooling is a viable and sustainable technique for improving PV performance, particularly in regions with high solar irradiance and elevated temperatures.

Zubeer s et al. [23] examined the impact of low-concentration photovoltaics (LCPV) combined with water cooling on the performance of PV modules through both experimental and numerical approaches. The experimental setup involves using optical concentrators to focus sunlight on PV modules at low concentration ratios, while a water-cooling system is employed to mitigate the associated temperature rise as illustrated in figure 4. The numerical model simulates the thermal and electrical behavior of the system to predict its performance under various operating conditions. Key experimental results indicate that the combination of low concentration and water cooling significantly enhances the power output and efficiency of the PV modules. Without cooling, the temperature of the PV module increases due to concentrated sunlight, leading to efficiency losses. With water cooling, the module's temperature is reduced by 10–25°C, depending on the concentration ratio and cooling rate. This temperature reduction improves electrical efficiency by 5–20% compared to modules operating without cooling. The numerical model aligns closely with experimental findings, providing insights into the optimal design of the cooling system, including flow rate and water distribution. The study highlights that low concentration combined with effective water cooling offers a cost-effective way to enhance PV performance, particularly in regions with high solar irradiance. It underscores the potential of integrating concentration and cooling technologies for more efficient and sustainable solar energy systems.

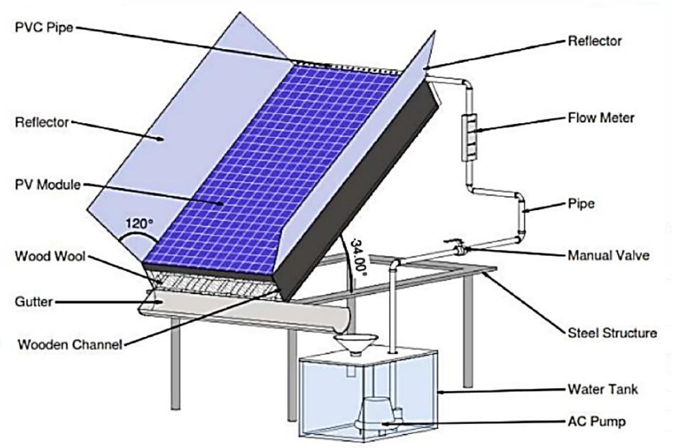

FIGURE 4. STRUCTURE OF THE EXPERIMENTAL SETUP[23].

S.M. Shalaby et al. [14] explored the effects of water cooling on the performance of photovoltaic (PV) panels. The methodology involved applying a thin film of water over the surface of the PV panel, and the system was tested under real outdoor conditions to assess the effectiveness of water cooling. The study measured several key parameters, including the panel's surface temperature, electrical efficiency, and power output, under both cooled and uncooled conditions. The cooling system used a continuous flow of water to maintain a lower surface temperature. The main results demonstrated that the water-cooling system significantly lowered the operating temperature of the PV panel, reducing it by up to 18°C. This temperature reduction resulted in an improvement in electrical efficiency of approximately 9% compared to the uncooled panel. Additionally, the power output of the cooled PV system was found to be consistently higher than that of the standard PV panel, confirming the positive impact of the water-cooling technique. The study concluded that water cooling is an effective method for enhancing PV performance, especially in hot climates where high temperatures reduce the efficiency of PV panels. Research in China has focused on hybrid PV/T systems that combine water cooling with thermal energy production.

Mehmet Ali et al. [24] investigated a water-based photovoltaic thermal (PV/T) system designed to enhance the performance of PV panels by cooling them while simultaneously capturing thermal energy. The methodology involved integrating a water circulation system with the PV panel, where water flowed beneath the panel to absorb excess heat generated during operation. This hybrid PV/T system not only cooled the panel but also allowed for the captured thermal energy to be used for heating purposes, improving overall system efficiency. The experimental setup included temperature sensors to monitor the cooling effect and power output measurements to assess performance improvements. The key results indicated a substantial reduction in PV panel temperature, with a cooling effect of up to 25°C compared to standard panels without cooling. This led to an improvement in electrical efficiency of approximately 15%, as the cooling mitigated the negative impact of high temperatures on PV performance. Moreover, the system was able to generate useful thermal energy, contributing to a more sustainable energy solution by combining electrical and thermal outputs in one system. The water-based cooling was particularly effective in hot climates, making it a promising technique for improving PV efficiency in areas with high solar irradiance. Some researchers have explored the use of graywater or rainwater for PV cooling, reducing the environmental impact of water consumption.

A case study in Australia by Md. Shahariar Chowdhury et al. [25] demonstrated the feasibility of using rainwater collection systems to supply water for PV panel cooling in residential installations.

4. Humidified Air-Cooling of PV Panels

Humidified air-cooling is an emerging technique that takes advantage of evaporative cooling to lower the surface temperature of PV panels. By increasing the humidity of the air flowing over the surface of the PV panels, water evaporates, absorbing heat from the panels in the process. This cooling mechanism is particularly effective in dry and hot climates where the potential for evaporative cooling is high.

Unlike water cooling, which involves direct contact between water and the panels, humidified air-cooling offers an alternative that avoids the potential issues of soiling, corrosion, and water wastage. It can be implemented using both passive and active methods, depending on the design and the scale of the PV system.

4.1. Mechanisms of Humidified Air Cooling

Humidified air-cooling works by utilizing the natural process of evaporation. When water evaporates, it absorbs a significant amount of latent heat from its surroundings, resulting in a cooling effect. In a humidified air-cooling system for PV panels, this principle is applied by adding moisture to the air that flows over the panel surface.

In dry climates, where the relative humidity of the air is low, the cooling effect can be maximized as the air can hold more moisture. The water vapor in the air absorbs heat from the PV panels, which helps to lower the panel temperature and improve overall efficiency. The cooling efficiency depends on factors such as air temperature, humidity, and the rate of airflow over the panel surface.

There are two main types of humidified air-cooling systems: passive humidified air-cooling and active humidified air cooling.

4.2. Passive humidified air-cooling systems:

In passive humidified air-cooling systems, the cooling effect is achieved without the use of external energy inputs like fans or pumps. These systems rely on natural airflow and the inherent ability of the surrounding environment to support evaporation.

4.2.1. Design Principles:

- Passive humidified air-cooling systems typically involve the use of wet or porous materials that can hold water, as illustrated in figure 5. These materials are placed close to the PV panels, and as the water in the material evaporates, it cools the air around the PV panel.

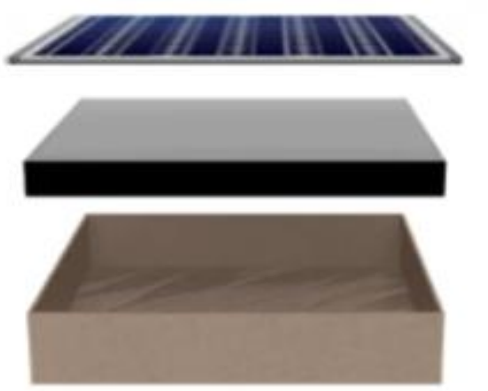

FIGURE 5. PV PANEL ATTACHED TO POROUS PAD [26].

- Materials such as sponges, fabric, or wicking materials are often used to increase surface area and promote evaporation. The evaporative cooling effect then lowers the temperature of the PV panels, resulting in higher electrical efficiency.

4.2.2. Advantages:

- No Energy Consumption: Since passive systems do not require any external energy to operate, they are highly efficient in terms of energy use.
- Simplicity: These systems are relatively simple to design and install, requiring minimal infrastructure and maintenance.
- Water Efficiency: Passive systems use small amounts of water, as they rely on the natural evaporation process. In some cases, rainwater or condensate water from nearby structures can be used to supply the cooling system.

4.2.3. Limitations:

- Lower Cooling Efficiency: Passive systems tend to be less effective than active systems in reducing PV temperatures because the airflow is not controlled, and the cooling capacity is limited by the rate of natural evaporation.
- Climate Dependence: The effectiveness of passive humidified air-cooling is highly dependent on the local climate. It works best in dry and arid regions, but its effectiveness is reduced in humid climates where the air is already saturated with moisture.

4.3. Active Humidified Air-Cooling Systems:

Active humidified air-cooling systems involve the use of mechanical systems, such as fans, to enhance airflow over the PV panels and improve the cooling effect. These systems are designed to maintain a continuous supply of humidified air over the panel surface, ensuring more efficient and consistent cooling.

4.3.1. Design Principles

- In active systems, air is circulated over the PV panels using fans, and moisture is added to the air through evaporative pads or misting nozzles, as shown in figure 6. The humidified air absorbs heat from the panels as it passes over the surface, cooling the panels more effectively than passive systems.

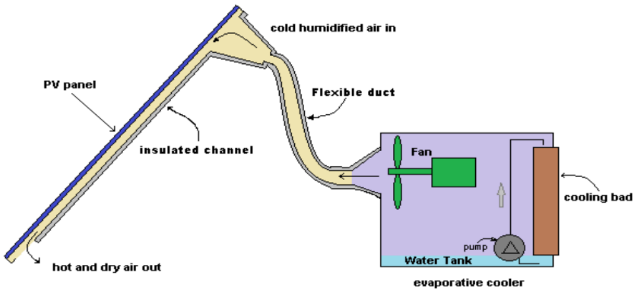

FIGURE 6. ACTIVE PV HUMIDIFIED AIR COOLING [36].

- The use of evaporative pads, like those used in cooling towers, increases the surface area for evaporation, allowing for greater cooling efficiency. In some systems, water misting is directly applied to the air stream, further enhancing the cooling effect.

4.3.2. Advantages

- Higher Cooling Efficiency: Active systems can reduce PV panel temperatures more effectively than passive systems, leading to greater efficiency gains in power output.

- Controlled Environment: By using fans to regulate airflow, active systems can maintain a more consistent cooling effect, even in variable weather conditions.

- Scalability: Active humidified air-cooling systems can be scaled to larger PV installations, making them suitable for both residential and commercial applications.

4.3.3. Limitations

- Energy Consumption: Active systems require energy to operate fans, pumps, and other components, which can offset the gains in electrical efficiency. However, the energy used for cooling is typically much lower than the increase in power output due to the cooling effect.

- Water Use: While humidified air-cooling systems use less water than direct water-cooling methods, they still require a steady supply of water to maintain the cooling process. In arid regions, this may present a challenge.

- Installation and Maintenance Costs: The additional infrastructure required for active systems, including fans, pumps, and evaporative pads, increases the overall cost of installation and maintenance.

4.4. Recent Research and Case Studies on Humidified Air Cooling

Several experimental studies and real-world applications have demonstrated the effectiveness of humidified air-cooling systems in enhancing PV performance. Some notable research findings include:

Research conducted in desert climates, such as the southwestern United States and the Middle East, has shown that active humidified air-cooling can reduce PV panel temperatures.

Abdul Hai Alami [27] investigated using passive evaporative cooling to reduce the operating temperature of photovoltaic (PV) modules. The study proposes a novel approach where a thin film of water is allowed to evaporate from a synthetic clay layer attached to the back of the PV module. This method is designed to lower the temperature without requiring active mechanical components, making it environmentally friendly, cost-effective, and low maintenance. The results demonstrate significant improvements in PV performance. The cooling system achieved a maximum temperature reduction, leading to an increase in output voltage by 19.4% and output power by 19.1%. The study highlights the feasibility of this approach for improving the energy efficiency of PV modules, especially in high-temperature environments.

Haidar et al. [28] investigated the use of evaporative cooling to enhance the efficiency of photovoltaic (PV) panels. This study employs a theoretical model to analyze heat and mass transfer processes near the bottom side of the PV panels. The model incorporates the interactions between a thin water layer, ambient air, and the PV surface, considering parameters such as airflow rate, temperature, and humidity. The results highlighted that lower air inlet temperatures significantly reduce PV panel surface temperatures. By optimizing conditions, the study demonstrated how evaporative cooling can effectively mitigate thermal losses, thereby improving the performance of PV systems, especially in hot climates.

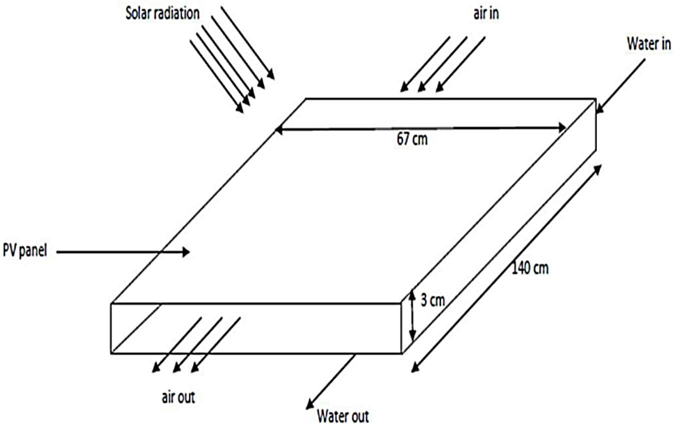

FIGURE 7. SCHEMATIC DIAGRAME FOR THE PV PANEL WITH EVAPORATIVE COOLING[28].

Lucas, M. et al. [29] investigated an innovative cooling method that combines the principles of evaporative cooling with the design of a solar chimney. The experimental setup included two photovoltaic (PV) modules: one as a control and the other modified with an evaporative solar chimney on its rear side as shown in figure 8. The cooling system employed water atomization using spray nozzles at the chimney's base, which facilitated evaporative cooling as air ascended through the chimney. The study monitored key parameters such as temperature, humidity, wind speed, and irradiance to assess the system's performance. Results indicated a reduction in PV module temperature by up to 8°C under typical Mediterranean summer conditions, leading to electrical efficiency improvements ranging from 4.9% to 7.6% at midday. The system was also capable of dissipating up to 1500 W of thermal power with a thermal efficiency exceeding 30% during peak summer months.

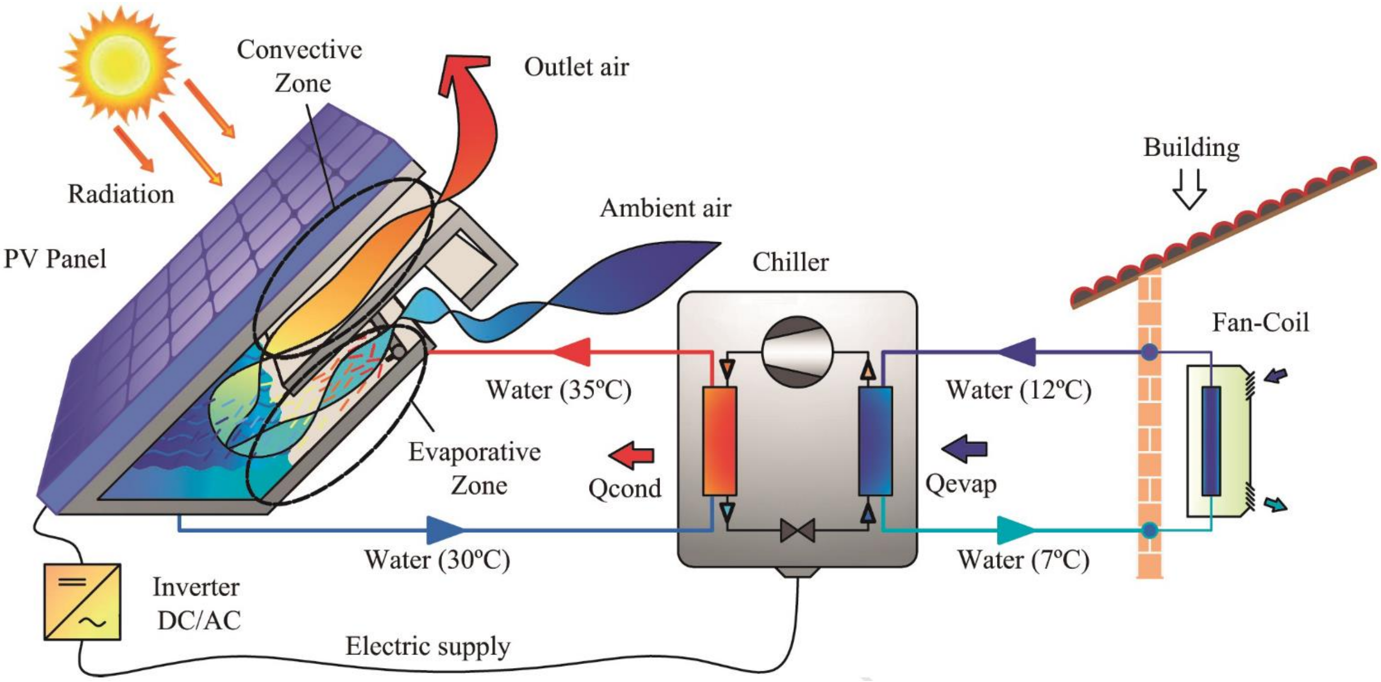

FIGURE 8. EVAPORATIVE PV SOLAR CHIMNEY AND AIR CONDITIONING SYSTEM[29].

Haidar, et al. [31] investigated a novel evaporative cooling (EC) system designed to regulate PV panel temperatures and improve their performance. The researchers developed and validated a heat and mass transfer model alongside experimental evaluations conducted under real environmental conditions. The EC system applied to the back surface of the PV panels, achieved a temperature reduction of up to 10°C, corresponding to a 5% enhancement in electrical power output. The study highlighted the cooling system's effectiveness in maintaining stable temperatures and enhancing energy generation, particularly in hot and arid climates, while optimizing water consumption to ensure the system's practicality for widespread use.

Žižak, Tej et al. [32] explored the use of evaporative cooling to enhance the performance and sustainability of photovoltaic (PV) systems. The researchers conducted in-situ experiments to model the PV cell temperatures and the convective heat transfer coefficients under varying conditions. The cooling method reduced peak PV temperatures by up to 20.1°C, which resulted in an electric power increase of up to 9.6%. The study also assessed the feasibility of sustainable cooling across different climates. For example, in temperate and continental climates, such as in certain European cities, (1–3) m² of roof area and (50–150) liters of rainwater storage per m² of PV are sufficient for year-round operation, leading to an annual electricity production increase of 5.9–9.4 kWh/m² (equivalent to a 3.6–4.6% improvement). However, in semi-arid climates like Lampedusa, larger roof areas and storage of up to 500 liters per m² are required, making implementation more challenging. In extreme desert climates, such as Almeria and Athens, sustainable evaporative cooling was deemed infeasible due to water scarcity.

Hamed et al. [33] presented a hybrid system that integrates photovoltaic (PV) thermal regulation with water harvesting using a silica gel layer facilitated by evaporative cooling. The methodology focuses on the dual functionality of silica gel, leveraging its high-water adsorption capacity to regulate the PV panel's temperature while simultaneously enabling water recovery from the atmosphere. The system operates by first adsorbing water vapor onto the silica gel layer, which then evaporates under controlled conditions to cool the PV surface. Key results demonstrate significant enhancements in PV performance due to reduced operating temperatures, alongside the production of usable water. The integration of the silica gel layer achieves a reduction in PV panel temperature by several degrees Celsius, leading to a marked increase in electrical efficiency, typically in the range of 5–10%, depending on the ambient conditions. Furthermore, the system captures and condenses water, yielding a practical solution for water-scarce regions while improving PV system reliability. This hybrid approach not only addresses the challenge of PV thermal regulation but also offers a sustainable pathway for water resource generation, particularly in arid and semi-arid environments. It highlights the potential of integrating adsorption-based materials into renewable energy systems for multifaceted benefits.

Alktranee et al. [34] conducted an energy and exergy analysis of photovoltaic (PV) modules integrated with evaporative cooling techniques to enhance their performance. The methodology involves applying evaporative cooling methods, such as water spraying or wetted surfaces, to maintain lower PV module temperatures during operation. Energy analysis focuses on quantifying the improvement in electrical output, while exergy analysis evaluates the system's thermodynamic efficiency by accounting for irreversibility and lost work potential. The results reveal that evaporative cooling significantly reduces the PV surface temperature, typically by 10–20°C depending on the cooling approach and ambient conditions. This temperature reduction leads to an increase in electrical efficiency, ranging from 5% to 15%, compared to uncooled modules. Exergy efficiency, which is inherently lower than energy efficiency, improves by approximately 3–8%, highlighting a more effective utilization of the available solar energy. The study underscores the thermodynamic advantages of evaporative cooling, particularly in hot climates, where elevated temperatures degrade PV performance. By combining energy and exergy analyses, the research provides a comprehensive understanding of the cooling technique's benefits and guides the design of optimized systems for enhanced PV performance and sustainability.

Chea.T et al. [35] investigated a photovoltaic (PV) module integrated with an evaporative cooling system, combining experimental analysis with modeling to evaluate performance improvements. The experimental setup involves applying a water film or wetted surface onto the PV module to facilitate evaporative cooling, thereby lowering the module's temperature during operation. The model developed incorporates thermal and electrical parameters to predict the temperature distribution, cooling effects, and corresponding improvements in efficiency under varying environmental conditions. The experimental results demonstrate that the evaporative cooling system effectively reduces the PV module temperature by 10–15°C compared to an uncooled module. This temperature reduction leads to an increase in electrical efficiency by 5–12%, depending on factors like solar irradiance, ambient temperature, and water application rate. The model shows good agreement with experimental data, confirming its reliability for predicting system performance across different scenarios. The integration of experimental data and modeling offers valuable insights into optimizing the cooling system, such as selecting appropriate water flow rates and evaporation dynamics.

Yang et al. [36] explored the use of dew-point evaporative cooling as an effective method for enhancing photovoltaic (PV) panel performance. This approach involves leveraging the cooling potential of air near its dew point, using water evaporation to lower the PV panel temperature without direct water application on the module's surface. The system is designed to circulate air across or beneath the PV panels, cooling them by utilizing evaporative heat exchange principles. Experimental and theoretical analyses reveal that dew-point evaporative cooling achieves a substantial reduction in PV panel temperature, typically by 10–20°C, depending on ambient conditions, humidity levels, and airflow rates. This temperature reduction results in a notable improvement in electrical efficiency, typically in the range of 5–15%, as well as increased power output. The dew-point method also minimizes water consumption compared to conventional evaporative cooling, making it more sustainable for water-scarce regions. A study by Alrashedy et al [36] used a 1/3 HP evaporative cooler to generate cool, humidified air passed through an insulated channel to reduce the PV panel's temperature in hot and dry climates like Aswan. Due to the effectiveness of evaporative cooling in low-humidity environments. The results showed that the cooling system had a notable impact on the PV panel's performance. Temperature reductions were achieved, which led to increases in electrical output. Specifically, the cooling helped to lower the panel's temperature, enhancing the electrical performance and efficiency of the panel. The system was designed to be energy-efficient, operating intermittently to maintain optimal panel temperatures. The study was conducted under real-world conditions, with data collected on solar radiation, current, voltage, and temperature throughout the day. It also included uncertainty analysis for precise measurements of output power and efficiency.

4.5. Advantages of Humidified Air Cooling

- Reduced Water Consumption: Compared to traditional water-cooling systems, humidified air-cooling uses less water, making it a more sustainable option in regions where water is scarce.

- Higher Efficiency Gains in Dry Climates: Humidified air-cooling is particularly effective in dry, hot climates where the relative humidity is low. The cooling effect can significantly improve PV panel efficiency in such environments.

- Low Maintenance: Passive humidified air-cooling systems require minimal maintenance, as there are no mechanical parts involved. Even active systems, while more complex, tend to have lower maintenance requirements than full water-cooling systems.

- Avoids Direct Contact with PV Panels: Because the cooling mechanism relies on air rather than direct water contact, there is no risk of soiling or corrosion of the PV panels.

4.6. Limitations and Challenges

- Dependent on Climate: The effectiveness of humidified air-cooling is highly dependent on the local climate. In areas with high humidity, the cooling effect is diminished, as the air cannot absorb as much moisture. This limits the application of this technique in tropical or coastal regions.

- Energy Use in Active Systems: The energy required to power fans and pumps in active systems can offset some of the efficiency gains achieved through cooling. Careful design is necessary to ensure that the energy consumption of the system is justified by the increase in PV panel output.

- Initial Cost and Infrastructure: Installing active humidified air-cooling systems requires additional infrastructure, including fans, ducts, and evaporative pads. This increases the initial cost of the system and may require specialized maintenance.

5. Comparative Analysis of humidified Air Cooling with Water Cooling

Humidified air-cooling and water cooling are two distinct approaches to managing the temperature of PV panels, each with its advantages and challenges. In general, water cooling tends to provide a greater cooling effect, making it more suitable for regions with abundant water resources. However, humidified air-cooling is more sustainable in water-scarce areas and offers comparable efficiency gains under the right conditions.

Some key differences include:

- Cooling Efficiency: Water cooling typically results in a larger temperature drop, especially in direct spraying or immersion systems. However, active humidified air-cooling can provide comparable results in arid climates with low humidity.
- Water Consumption: Water cooling systems generally consume more water than humidified air-cooling systems. This makes humidified air-cooling more suitable for regions with limited water availability.
- Complexity and Cost: Active humidified air-cooling systems are less complex and costly than water cooling systems, particularly those that rely on pumps and large-scale water distribution systems. However, passive humidified air systems are the most cost-effective option in terms of both installation and operation.

Summarizing these results, we can highlight the main advantages and disadvantages of each cooling method, including evaporative cooling and water cooling, in the following table, table.1.

Table 1 SUMMARY OF THE ADVANTAGES AND LIMITATIONS OF DIFFERENT COOLING METHODS FOR BOTH WATER AND EVAPORATIVE COOLING

Water Cooling of PV Panels	Surface Water-Cooling (Spraying or Immersion)	Advantages	• Low cost • Cleaning the panel surface by reducing dust accumulation.
		Limitations	• Accelerate the degradation of PV materials due to corrosion • Regular maintenance
	Water Circulation Beneath the Panels	Advantages	• Avoids direct contact between water and PV surfaces • Extending the life of the panels • Integration with existing panel designs
		Limitations	• Low efficiency of heat transfer compared to direct spraying • Adding complexity and cost to the system
	Hybrid PV/Thermal (PV/T) Systems	Advantages	• Enhance the total energy yield of the system • Improving the economic viability of PV systems
		Limitations	• More complex and costly to install and maintain • Hard to balance the electrical efficiency of the PV panels with the thermal efficiency of the heat absorber
Humidified Air-Cooling of PV Panels	Passive humidified air-cooling systems	Advantages	• No Energy Consumption • Simplicity • Water Efficiency
		Limitations	• Lower Cooling Efficiency • Climate Dependence
	Active Humidified Air-Cooling Systems	Advantages	• Higher Cooling Efficiency • Controlled Environment • Scalability
		Limitations	• Energy Consumption • Water Use • Installation and Maintenance Costs

6. Advanced Cooling Technologies

As the demand for efficient solar energy systems continues to grow, researchers and engineers are exploring innovative cooling techniques that go beyond traditional water and air-cooling methods. These advanced cooling technologies aim to enhance the performance of PV panels while addressing limitations such as water scarcity, energy consumption, and installation complexity. This section will focus on novel materials, nanotechnology, hybrid systems, and emerging trends in passive and active cooling solutions.

6.1. Phase Change Materials (PCMs) for Cooling PV Panels

Phase change materials (PCMs) have gained significant attention as a passive cooling solution for PV panels. PCMs absorb heat when transitioning from solid to liquid and release heat during the reverse process, thereby regulating the temperature of the panels without requiring active energy inputs. This thermoregulation helps maintain the panels at an optimal operating temperature, leading to higher efficiency and longer panel lifespan.

Ciril Arkar et al. [37] investigated two passive cooling methods for PV systems: phase change materials (PCM) and evaporative cooling. The research evaluates these methods for their effectiveness in mitigating PV overheating under high-temperature conditions. The PCM-based system leverages the latent heat of phase change to absorb thermal energy, stabilizing the PV panel's temperature. Meanwhile, evaporative cooling uses water's heat absorption during evaporation to achieve cooling. Both techniques are assessed through computational and experimental analyses to identify their impact on temperature regulation, energy output, and overall system efficiency. Key findings include the superior cooling effect of the evaporative system in arid climates due to its ability to lower PV temperatures more effectively during peak sunlight hours. However, PCM systems offer long-term thermal stability with minimal maintenance. The study highlights the trade-offs between water consumption and maintenance for evaporative cooling and the initial cost of PCM materials, suggesting appropriate applications based on climatic and operational conditions

6.1.1. Working Principle

- PCMs work by utilizing the latent heat of phase change. When the temperature of the PV panel rises, the PCM absorbs heat and melts, maintaining the panel temperature at the material’s melting point. When the temperature drops, the PCM solidifies, releasing the stored heat.

- Common PCMs used in PV cooling systems include paraffin wax, fatty acids, and hydrated salts, which have specific melting points tailored to the operational temperature range of PV panels.

Integration with PV Systems

- PCMs can be integrated into the rear surface of the PV panels or housed in heat sinks attached to the panels. The materials are typically encapsulated in containers or structures that facilitate heat transfer and prevent leakage during the phase change process.

- Some PV panels are designed with built-in PCM reservoirs, while others use external cooling units that house the PCM, ensuring compatibility with various types of PV installations.

6.1.2. Advantages

- Energy-Free Cooling: PCMs provide cooling without consuming electricity, making them an ideal passive cooling solution.

- Consistent Temperature Control: By absorbing excess heat during peak sunlight hours, PCMs help maintain stable temperatures, even during periods of high irradiance.

- Extended Panel Lifespan: Reducing temperature fluctuations extends the lifespan of PV panels, as overheating can accelerate material degradation over time.

6.1.3. Challenges and Limitations

- Material Cost and Availability: High-quality PCMs can be expensive, and the availability of materials with suitable melting points and thermal properties is limited.

- Thermal Conductivity: Most PCMs have relatively low thermal conductivity, which can limit their ability to transfer heat quickly. Advanced designs often incorporate thermally conductive additives, such as graphite or metal foams, to enhance heat transfer.

- Encapsulation Challenges: Encapsulating PCMs in leak-proof and durable containers that allow for efficient heat exchange is technically challenging, especially in outdoor environments where durability is critical.

6.2. Nanofluids for Enhanced Cooling

Nanofluids—fluids containing suspended nanoparticles—have been explored as a potential cooling medium for PV systems due to their superior thermal properties. Nanofluids exhibit higher thermal conductivity than conventional fluids like water or air, enabling them to absorb and dissipate heat more efficiently. By circulating nanofluids in a cooling loop around or within the PV panels, the system can achieve better heat transfer and reduce panel temperatures more effectively.

6.2.1. Composition and Properties

- Nanofluids are typically composed of base fluids (e.g., water, ethylene glycol) and nanoparticles made from materials such as metals (e.g., copper, silver), metal oxides (e.g., aluminum oxide), carbon nanotubes, or graphene. The addition of nanoparticles increases the thermal conductivity, heat capacity, and overall cooling performance of the fluid.

- The size, concentration, and type of nanoparticles used directly impact the effectiveness of the nanofluid. Research has shown that smaller nanoparticles with high thermal conductivity materials (such as copper or graphene) provide the best cooling performance.

6.2.2. Application in PV Cooling

Nanofluids can be used in both passive and active cooling systems for PV panels. In passive systems, nanofluids may be applied in heat sinks or panels' rear surfaces to passively absorb heat. In active systems, they are circulated through cooling channels or pipes in direct contact with the panels.

Murtadha et al. [38] explored the use of aluminum oxide (Al_2O_3) nanofluid as a cooling medium to optimize the performance of photovoltaic (PV) panels, examining the effects of varying nanoparticle concentrations within a one-pass flow system. Both experimental and theoretical analyses were conducted to evaluate the impact of nanofluid-based cooling on the panel's temperature, electrical efficiency, and power output. Results show that Al_2O_3 nanofluid significantly reduces PV panel temperatures compared to conventional water cooling, with reductions ranging from 10 to 25°C under typical solar irradiance conditions. The temperature decrease leads to notable improvements in electrical efficiency, increasing by 5–15% depending on the nanoparticle concentration. The enhanced thermal conductivity of the nanofluid ensures effective heat transfer, keeping the PV module within its optimal operating range. Power generation is also significantly improved, with increases of 10–20% observed, as the cooling system minimizes thermal losses and stabilizes the panel's output. The study identifies an optimal nanoparticle concentration that balances thermal performance with practical considerations, such as viscosity and pumping power requirements. While higher concentrations of nanoparticles improve cooling, they also increase the viscosity of the fluid, potentially raising the energy demand for fluid circulation. The one-pass flow system used in the research provides efficient heat removal across the panel's surface, offering a straightforward yet highly effective cooling strategy without the need for complex recirculation setups. These findings underscore the potential of Al_2O_3 nanofluid as a superior cooling fluid for PV panels, particularly in high-temperature environments. By optimizing nanoparticle concentration and flow system design, the study presents a sustainable and efficient approach to enhance the longevity and performance of PV systems. Some experimental setups involve nanofluid-based radiators, where the fluid absorbs heat from the PV panels and releases it into the environment as it circulates through a cooling loop.

6.2.3. Advantages

- Superior Heat Transfer: Nanofluids have significantly higher heat transfer capabilities compared to traditional fluids, making them highly effective for PV panel cooling.
- Tailored Thermal Properties: The composition of nanofluids can be customized to meet the specific cooling needs of different PV installations, optimizing performance for various environmental conditions.
- Potential for Hybrid Systems: Nanofluids can be integrated into hybrid cooling systems that combine both water and air-cooling methods, further enhancing overall efficiency.

6.2.4. Challenges and Limitations

- Cost and Availability: The production of nanofluids, particularly those containing high-quality nanoparticles, can be costly, limiting widespread adoption.
- Stability: Nanoparticles can aggregate and settle over time, reducing the effectiveness of the nanofluid. Stabilizing agents and advanced formulations are required to maintain the suspension.
- Environmental Concerns: The long-term environmental impact of using nanomaterials in large-scale solar installations is still under study, particularly in terms of potential nanoparticle leakage and contamination.

6.3. Hybrid Cooling Systems

Hybrid cooling systems combine two or more cooling techniques to maximize the efficiency of PV panels. By integrating both passive and active cooling mechanisms, hybrid systems can achieve superior performance compared to individual cooling methods. For instance, water cooling and air-cooling can be combined in a system that first cools the panels with water and then enhances the cooling effect using airflows to evaporate the residual moisture.

6.3.1. Water-Air Hybrid Systems

- In water-air hybrid systems, water is sprayed or circulated over the PV panels to absorb heat, and the resulting evaporative cooling effect is enhanced by airflow. This approach reduces both panel temperature and water consumption, making it suitable for regions with limited water resources.
- Some designs include water misting systems combined with air blowers to maximize the cooling effect without excessive water usage. The water evaporates rapidly due to airflow, reducing the amount of water needed to achieve significant cooling.

6.3.2. PCM-Air Hybrid Systems

- Another hybrid approach involves using phase change materials (PCMs) in conjunction with air cooling. As the PCMs absorb heat and transition to a liquid state, airflows pass over the panel, enhancing heat dissipation from the PCM and improving overall cooling efficiency.
- This system benefits from the passive cooling properties of PCMs while leveraging active airflow to prevent the PCM from overheating or saturating.

6.3.3. Nanofluid-Based Hybrid Systems

- Some experimental PV cooling systems incorporate nanofluids in combination with traditional water cooling or air-cooling techniques. The superior heat transfer properties of nanofluids help to enhance the cooling performance of the system while minimizing water usage and maximizing thermal efficiency.

➢ *Advantages of Hybrid Systems*

- Maximized Cooling Efficiency: By combining different cooling techniques, hybrid systems can achieve greater temperature reductions than any single method, leading to higher PV efficiency.

- Adaptability: Hybrid systems can be tailored to different climates and operational conditions, ensuring optimal performance in a variety of environments.

- Water Conservation: Hybrid systems that use air-cooling to enhance water cooling can significantly reduce water consumption, making them ideal for arid regions.

➢ *Challenges and Limitations*

- Increased Complexity: Hybrid systems are more complex to design, install, and maintain than single-method cooling systems. This increases both the initial cost and the operational requirements of the system.

- Energy Consumption: Active components in hybrid systems, such as fans and pumps, require energy to operate, which can offset some of the efficiency gains from cooling. Careful design is needed to balance energy use and cooling performance.

- Cost: The integration of multiple cooling technologies increases the overall cost of the system, both in terms of installation and maintenance. However, this cost can be justified by the long-term efficiency gains.

6.4. Emerging Trends in PV Cooling

Several innovative cooling technologies are currently being researched and developed, with the potential to revolutionize the way PV panels are cooled and enhance solar energy production. Some of the most promising trends include:

6.4.1. Radiative Cooling

- Radiative cooling takes advantage of the natural emission of heat as infrared radiation from the surface of PV panels. By designing panels with materials that maximize radiative heat loss, this method allows panels to cool themselves by emitting heat into the atmosphere, especially during the night or in low-sunlight conditions.

- Some researchers are exploring coatings and materials that can enhance radiative cooling during the day while still allowing the panels to absorb sunlight efficiently.

6.4.2. Heat Pipe-Based Cooling

Heat pipes are passive heat transfer devices that use the phase change of a working fluid (typically water) to move heat away from the PV panel. The heat is absorbed by the evaporating fluid and transferred to a condenser, where it is dissipated into the environment.

- Heat pipes offer a compact and efficient cooling solution, and they can be integrated into PV modules or external cooling units.

6.4.3. Thermoelectric Cooling

- Thermoelectric coolers (TECs) use the Peltier effect to generate a temperature difference when an electric current flows through them. TECs can be applied to PV panels to actively cool them by absorbing heat from the panel and dissipating it into the environment.

- While thermoelectric cooling requires energy input, the energy consumption is relatively low, and TECs can be powered by the electricity generated by the PV panels themselves.

7. Conclusion

Photovoltaic (PV) panel efficiency is significantly influenced by temperature, with excessive heat reducing power output and overall system performance. To mitigate this issue, evaporative cooling and water cooling have emerged as effective solutions for enhancing PV efficiency.

Evaporative cooling is a highly effective method for reducing the operating temperature of PV panels, particularly in hot and arid climates where air moisture content is low. This method leverages the latent heat of vaporization, where water absorbs heat from the PV panel and evaporates, thereby cooling the surface. Studies have demonstrated temperature reductions of up to 15°C, leading to 5-10% efficiency gains. Additionally, evaporative cooling operates with minimal energy input, making it a sustainable and cost-effective solution that does not significantly increase system energy consumption. By maintaining lower temperatures, this method reduces thermal stress on PV modules, improving their lifespan and long-term performance. Furthermore, utilizing natural water evaporation makes this an eco-friendly cooling approach with no direct carbon footprint or emissions.

Water cooling is another effective approach for PV thermal management, particularly in high-irradiance regions where direct cooling methods are required. Water is an excellent heat absorber, and when applied directly to PV panels, it can significantly lower surface temperatures, preventing overheating and efficiency losses. Research indicates that water cooling can improve PV efficiency by 10-15%, outperforming conventional passive cooling methods. Additionally, water cooling can be integrated into photovoltaic-thermal (PVT) systems, allowing simultaneous electricity generation and hot water production, increasing the overall system's energy yield. Running water over PV panels also helps in reducing dust accumulation and soiling effects, which otherwise reduce light absorption and system performance.

In conclusion, thermal management plays a crucial role in optimizing PV system efficiency. Both evaporative cooling and water cooling provide significant advantages in improving PV panel efficiency and longevity. Evaporative cooling is most suitable for hot and dry climates where natural evaporation is highly effective, while water cooling is ideal for intensive cooling applications where maintaining lower temperatures is critical. Integrating these cooling techniques into PV systems can result in substantial performance improvements, making them essential solutions for maximizing energy output in challenging environmental conditions. Future research should focus on optimizing these cooling methods for large-scale implementation and assessing their long-term economic and environmental impacts.

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