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Comparative Study of Cooling Techniques for Photovoltaic Panels: Active Cooling Techniques, A Review

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Abstract

The primary goal of photovoltaic panels is to generate electricity. The efficiency of solar systems, in particular photovoltaic panels, is generally low. The performance of PV panels depends on many parameters, such as temperature. Studies have shown that panel efficiency decreases at a rate of (0.45 - 0.65) per one degree Celsius, so the decrease in temperatures of the photovoltaic cell leads to Higher performance, and therefore requires keeping the photocell as cool as possible. This can be achieved through the cooling system, which not only enhances the electrical efficiency of the PV module but also reduces its rate of deterioration over time, thus extending its life. In addition, the excess heat removed by the cooling system can be used in many applications. There are many cooling technologies available, including the use of air or water as the working fluid with motion generated by the circulation of the water, forced water heat exchanger, water mist, or the use of fans to circulate air. The cooling process using water is more effective than air, as the average temperature decreases from (9-17) degrees Celsius. This paper presented a review of relevant literature on active cooling for thermal regulation and electrical efficiency enhancement of PV modules. Research conducted in this field has shown that these techniques have been successfully applied to improve the efficiency of photovoltaic cells under various conditions.

Keywords: Photovoltaic cooling techniques; Active cooling porous media; Nano fluid; Air cooling; Water cooling

1. Introduction

Energy consumption is a good indicator of a country's economic development because it reflects the need for, and the progress toward, technical advancement and the maintenance of economic growth. The worldwide economy has expanded by 3.3% annually over the past 30 years. From 2010 to 2030, global energy usage is expected to rise by 33% [1]-[6]. Greenhouse gas emissions, especially carbon dioxide (CO2), have come under scrutiny as a result of growing environmental concerns related to the inefficient use of energy, climate change, acid rain, stratospheric ozone depletion, and the world's reliance on electricity. In order to decarbonize electricity generation, many industrialized countries are looking to replace conventional coal and fossil fuel-fired plants with renewable technology alternatives. This is because traditional power generations, which are based on fossil fuel, are generally considered to be unsustainable in the long term due to the shortage of inexhaustible resources and environmental problems caused by the emissions. Therefore, there are global initiatives and many nations have been increasing the percentage of their electricity generated by green sources like wind, solar PV, water, vegetation, ocean, etc. The use of photovoltaic cells is now widely considered a practical option [7]-[21]. Solar energy is important because it is readily accessible everywhere, can be scaled to meet varying requirements, and can be used in both grid-connected and off-grid settings [7]. Electrical energy and heat energy are both possible outcomes of harnessing the sun's rays. Photovoltaic (PV) cells can be used to generate electricity, and one of their advantages, is that it doesn't require lofty, sturdy structures, cause no shaking, and They require simple cooling systems, especially in the Middle East regions at certain times. In addition, it poses no threat to public health or the atmosphere and produces no harmful gases. Because of this, they have been used to power everything from computers and timepieces to water pumps and distant structures to communications satellites and spacecraft. Covering just 1% of Earth's surface with 10%

effective PV panels would generate twice as much energy as is needed today. Unfortunately, when PV cells are subjected to sunshine, only a tiny percentage of the solar energy is converted into usable power. As a practical matter, only 15% to 20% of the incident solar radiation can be converted into electricity, and more than 80% of the falling sunlight-based radiation is not converted into electrical energy [17],[18]. Sunlight is the only wavelength used by solar cells. incoming solar light between 380 and 700 nm (nanometers) to produce electricity, while the other wavelengths are converted into thermal energy, increasing the temperature of the cells and lowering the efficiency of the PV module [19],[20].

This article presents methods used to cool photovoltaic panels reviewed by methodologies for active cooling of photovoltaic cells, depending on the type of liquid used for active cooling of photovoltaic panels, i.e. air and water. The article focuses on the latest research and the scientists who contributed to it. There are many environmental factors that have an impact on solar panels. For example, sunlight, ambient surface temperature, module, wind speed, humidity, shading, dust, weather conditions, photocell direction, etc., the main players are indeed solar radiation and temperature. Finally, according to the methods reviewed and their impact on the efficiency of photovoltaic panels, some suggestions were made to further improve their efficiency and reduce their operating temperature.

2. A Working Principle of a Photovoltaic Cell, and How Temperature Affects How Well It Performs

Silicon-based photovoltaic (PV) technology is currently the most popular PV technology on the market, despite being the oldest PV technology. The main drawback of the most used silicone-based PV technology is its insensitivity to the temperature at which it operates scale, where the standard conditions under which photovoltaic cells are usually examined are typically analyzed (STC: 1000 W / m^2, 25° C temperature, and global 1.5 AM spectra) [21]-[22]. It is well known that the efficacy of PV solar cells declines with a rise in temperature; this is the primary impact of the process of turning solar energy into electrical energy in PV. Solar cell components' characteristics are, likewise. Since other PV technologies, including amorphous, CdTe, and CIS/CIGS, share this characteristic their average energy conversion efficiencies range from 6% to max. PV systems should be designed not only in consideration of the ambient temperature trend but also with a thorough understanding of the materials used in the PV panel. Fig. 1 [23] shows that sun energy, temperature, and conversion effectiveness have a significant impact on a PV system's output, which can vary by as much as 12% (relative to Si-mono or Si-poly PV systems). Specifically, a 0.4% to 0.5% decrease in energy conversion efficacy can be expected for every degree Celsius the working temperature of a PV panel is raised above its optimal range (less for amorphous siliceous technology, about 0.25%/°C). Therefore, a greater energy utilization rate could be guaranteed by restricting the working temperature of the PV panels. The open-circuit voltage of a solar cell or PV module is most sensitive to changes in temperature. As the temperature in a circuit rises, the resistance rises to reflect the increased velocity of the electrons. Therefore, refrigeration is necessary for PV cells to work efficiently. The exterior performance of PV cells is hindered by the high temps they attain in extreme irradiance circumstances during operation. It's possible for PV cells to get as hot as 60°C to 80°C. A solar cell's efficacy, as measured by its open- and short-circuit voltages, short-circuit currents, curve factors, and efficiencies, varies with temperature.

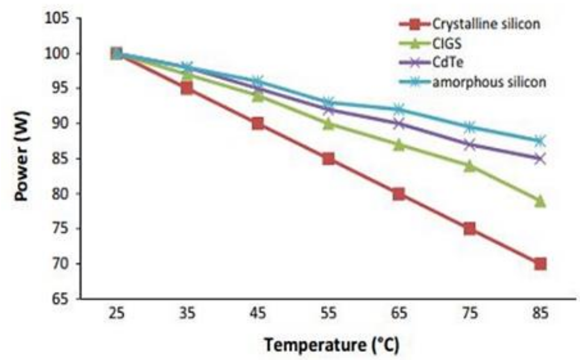


Figure 1. Influence of temperature on various PV materials. [23]

Voc decreases at a rate of 0.1%/°C as temperature (T) rises, and Isc rises very slightly, both of which contribute to a decline in cell efficacy [22][24]. Which photovoltaic device captures solar energy through the P-N junction of a photovoltaic cell when light strikes the cell from outside. When the charging vectors move, a solar current (IPV) is generated. The solar PV cell can be represented with an analogous electrical circuit, shown in Fig.2, characterized numerically by the formula (1, 2), where I is the current through the P-N diode.

$$I = -I_{SC} + I_o\left(e^{\frac{qV}{nKT}} - 1\right) \quad (1)$$

$$V_{OC} = \frac{nKT}{q}\ln\left(\frac{I_{SC}}{I_o} + 1\right) \quad (2)$$

Where I the output current in (A). T is inversely proportional with absolute temperature is (K), ideality factor, n, K the Boltzmann constant, 1.381*10^{-23}, and q the directly proportional with elementary charge, 1.6*10^{-9}.

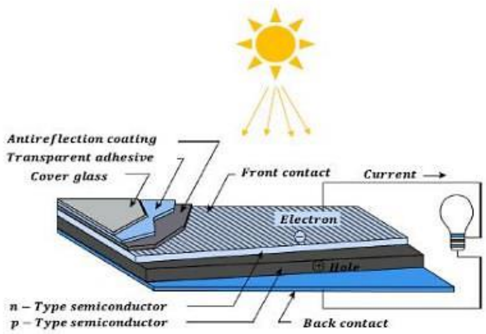
$$FF = \frac{P_m}{I_{SC}V_{OC}} = \frac{I_m V_m}{I_{SC}V_{OC}} \quad (3)$$

(FF) The fill factor, (Isc) short circuit current in (A), (Voc) open circuit voltage in (V), and highest power point (max) in the module's I-V graph are the variables in this calculation. Fig. 3 shows that as the temperature rises, the electrical characteristics of a semiconductor change: the open-circuit voltage and fill factor both declines, while the short-circuit current rises, albeit only slightly. Therefore, the overall result is a straight relationship.

$$\eta_e = \eta_{pv}[1 - \beta r(T_c - T_r)\gamma \log 10\, I_{array}] \quad (4)$$

Where: η_{pv} is the solar cell's efficacy measured at 25 degrees Celsius (Tr) as defined by standard circumstances. The cell effectiveness temperature parameter, ßr, is typically 0.004-0.005 per degree Celsius. At its normal working temperature, the average hourly radiation falling on the PV module is denoted by the symbol Ipv. TN. The PV module temperature, Tc, and the light intensity cell efficiency index are both measured in kelvins. The above equation is typically simplified by setting = 0, and it is used to determine how climate affects a solar cell according to [22,[25]-[27][:

$$\eta_e = \eta_{pv}[1 - \beta r(T_c - T_r)] \quad (5)$$



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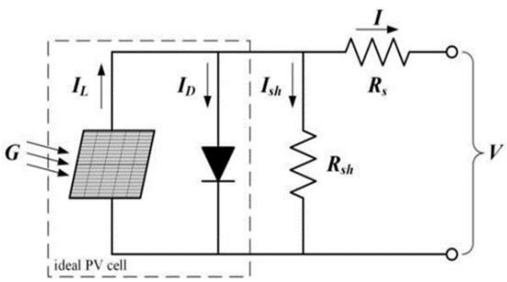
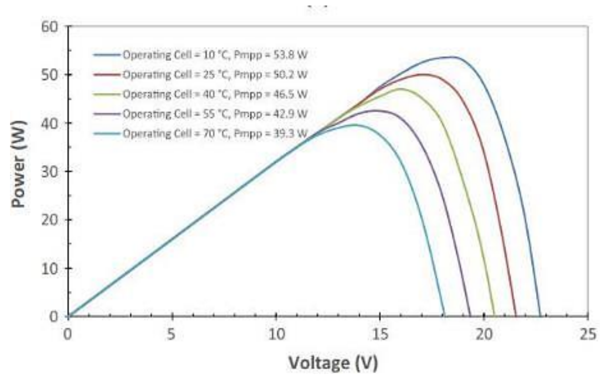


(a)

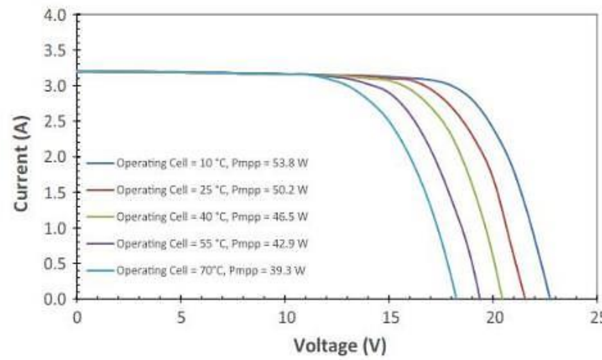
Figure 2. (a). The equivalent electrical circuit for a PV cell (b). The performance of a solar cell [27]

The decline in photovoltaic cell efficiency, which can range from 9% to 12% [28], highlights the need for feasible, simple, and low-maintenance solutions to enhance their suitability for alternative energy applications and technologies. The implementation of these solutions has the potential to mitigate the issue of elevated cell temperature, thereby enhancing the efficacy and output of the photovoltaic cell. It is imperative to thoroughly examine various techniques aimed at enhancing the efficiency of photovoltaic cells, as well as identify the key factors that impact their performance. Prior research conducted by numerous authors and scholars has yielded valuable insights, which will be presented in this paper. One such technique involves reducing board temperature through the implementation of cooling measures, which can significantly improve the electrical output of the module and mitigate thermal stress.

This review will focus on the most pertinent studies pertaining to previous research and cooling strategies for photovoltaic cells, as outlined in a previous review paper.



(a)



(b)

Figure 3. Features of (a) output I–V, (b) output P–V of the PV module at various temperatures [28]

Bahaidarah et al. [28] examined the significance of standardizing the cooling process for photoelectric systems and analyzed the economic and environmental implications of various cooling techniques. Specifically, a comparative case study is conducted to evaluate the cooling of photovoltaic systems using standard and non-standard methods. The study revealed that the implementation of the immersing photovoltaic technique resulted in a decrease in the temperature of photovoltaic systems to a range of 20-45°C specifically for concentrated photovoltaic systems. By utilizing the heat pipe technique, it was possible to reduce the temperature to 32°C while achieving a non-uniform temperature of 3°C. The objective of the study conducted by [29] is to enhance the operational efficiency of small-scale photovoltaic (PV) systems intended for household use. This is achieved by maintaining a consistent and minimal temperature of the PV cells. Different cooling techniques have been investigated experimentally and numerically the impact of the operating temperature of the cells on the electrical and thermal performance of the PV systems. This paper aims to analyze the efficacy of various cooling techniques, namely ribbed wall heat sink cooling, array air duct cooling installed beneath the PV panel, water spray cooling technique, and back surface water cooling, in terms of their impact on the performance of PV panels. Chandel and Agarwal [30] centered on the primary literature pertaining to photovoltaic cells and conducted a quantitative examination of the thermal equations governing the behavior of said cells. The majority of research aims to improve cellular performance and augment proliferation, the enhancement of productivity, and the extension of product lifespan. The study centered on the comparison between passive and active cooling systems. The comprehensive review suggests that the increasing global demand for solar PV electricity necessitates the implementation of a compatible cooling system to optimize energy harvest and utilization. Maleki et al. [31] pertained to the utilization of phase-change materials (PCM) to cool photovoltaic cells, with the aim of enhancing their efficiency and performance while minimizing costs. The primary objective is to ascertain crucial research domains that guarantee dependable functionality and economic feasibility of the technology. The findings indicate that the integration of phase-change materials (PCMs) with photovoltaic (PV) systems leads to a 5% improvement in the electrical efficiency of the cell. The issue pertaining to PCM pertains to its suboptimal thermal conductivity and its relatively elevated economic expenditure. This paper highlights certain gaps that were observed in the cooling process. The feasibility of PCM cooling technology is hindered by its high cost and limited availability of requisite materials. Alternative cooling technologies were explored and compared with PCM. This information is supported by reference [30].

The objective of this research was to conduct a comparative analysis of the most viable active cooling methods for photovoltaic systems. The study aimed to provide insights into the design, application, and future development of cooling techniques in this field. The findings suggest that future technology development should prioritize the development of hybrid cooling methods that can effectively maintain low and stable surface temperatures.

3. Classification of Cooling Techniques

Researchers are currently engaged in the development of cooling mechanisms aimed at mitigating the operational temperatures of solar cells. These cooling systems are classified as either active or passive. The enhancement of PV module performance is achieved through the utilization of both passive and active cooling techniques. Each of the various applied approaches for managing energy systems possesses its own set of benefits and drawbacks. Active methods offer a notable advantage in terms of their increased heat removal capacity, albeit at the cost of a more intricate structure necessitated by the need for supplementary equipment. Conversely, the primary benefits of passive methodologies lie in their uncomplicated configuration, absence of supplementary apparatus and equipment, and reduced maintenance expenses relative to active methodologies in the majority of instances. This is primarily attributed to the diminished quantity of equipment and media employed in passive approaches. As per a comparative analysis [32],[33].

3.1 Passive methods

Passive methodologies are highly applicable to PV cooling projects as well. The aforementioned techniques do not necessitate supplementary mechanical apparatus. Despite this, the primary benefit of passive methodologies is their independence from an external power supply to operate the cooling mechanism. Consequently, a reduction in complexity and a decrease in maintenance expenses are observed. Some of the most effective passive methods and their impact on cell performance. (Wick structure, Phase change material, Heat sink, fins, extended surfaces, heat exchanger, Radiative sky cooling) [28].

3.2 Active methods

The implementation of active cooling management techniques requires the utilization of external energy sources and supplementary equipment, such as fans or pumps, to facilitate the circulation of the cooling medium. These methods inherently require additional energy consumption and supplementary equipment and are more efficient in terms of enhancing heat transfer rates for cooling purposes. Some of the most effective passive methods and their impact on cell performance. (Forced water circulation, Forced Air cooling, Liquid cooling, Liquid spraying, Liquid immersion cooling, Nano-fluid, Thermoelectric (Peltier) cooling) [28]. The subsequent subsections provide an overview of the primary techniques employed for managing cell cooling.

3.2.1 Studies that to use of water as the working fluid in cooling

Water exhibits a high heat capacity and a favorable heat transfer coefficient. Water cooling technology is distinguished by its highly efficient cooling capabilities, which enhance the photovoltaic cell's conversion efficiency. The utilization of hot water generated from the cooling process has potential for various applications. The methodology of water cooling has undergone various advancements and it is feasible to provide an overview of the different forms of water cooling. The present study introduces and empirically assesses an active cooling methodology for photovoltaic panels.

The proposed technique involves the utilization of a water flow mechanism directed towards the frontal aspect of the PV panel. In their study, Odeh and Behnia [33] The cooling process was achieved by introducing a water trickling configuration on the upper surface of the panel while maintaining a constant cooling water flow rate of 4 l/min. (see Fig. 4).

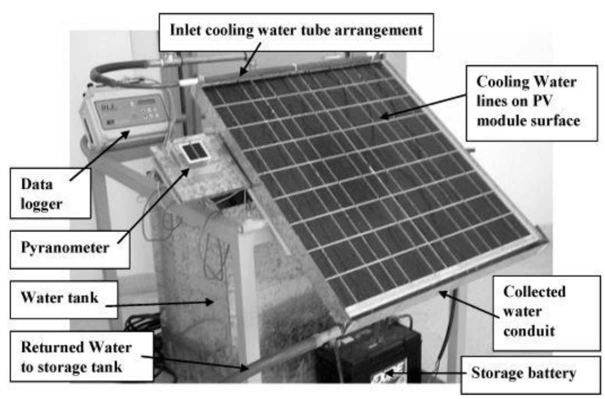


Figure 4. PV water cooling test rig.[33]

The results showed that the adoption of the system output increased within the range of 4-10%.

Salih et al. [34] developed and executed a technique involving forced water spraying and cooling with a constant flow rate of water on the surface of a photovoltaic array. The photovoltaic configuration consisted of five parallel modules situated at a latitude of 33.3° south. A notable increase in the power output of the photovoltaic (PV) cells resulted, with a power fluctuation of 0.107 W/°C. The average power output was increased by about 65 W when water spraying was applied. The rate of cooling during a 5-minute interval at noon was determined 4 °C/min. The average effectiveness of the spraying mechanism over the course of a 24-hour period was calculated to be 17.8 percent. The difference in water temperature was found to be 6.83°C during midday and 9.8°C at sunset.

Irwan and colleagues [35] established a solar simulator that was mounted on a steel frame to elevate the halogen lamp bulbs. Halogen lamp bulbs are capable of simulating natural sunlight. The primary aim of the solar simulator is to evaluate the efficacy of a photovoltaic (PV) panel, both with and without a water-cooling mechanism, in an indoor testing environment. The solar simulator measures four sets of average solar radiation at the test surface, which are recorded as 413, 620, 821, and 1016 W/m². The utilization of a DC water pump serves as a solution to the issue of low efficiency of photovoltaic (PV) panels when water is made to flow over their front surface. The experimental findings indicate that a decrease in operating temperature by approximately 5 - 23 ˚C results in a power output increase of 9 - 22% for a photovoltaic panel utilizing a water-cooling mechanism. (see Fig. 5).

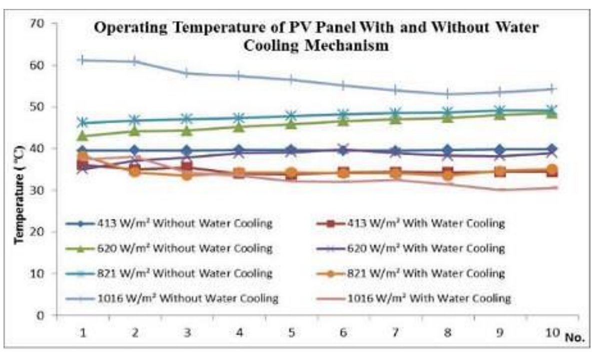


Figure 5. Operating temperature of PV panel with and without water cooling mechanism.[35]

In the absence of active cooling, the experimental setup and methodology employed in GEP modeling resulted in a 16.81% efficiency for the uncooled PV module. Nonetheless, under the circumstances of active cooling, the panel exhibited a considerable reduction in temperature, resulting in a corresponding enhancement in the efficiency of solar cells to approximately 18.83%.

Schiro et al. [36] devised a technique involving water spraying to cool photovoltaic (PV) modules. The cooling behavior of the PV system was examined under both steady and dynamic conditions. The temperature module was calculated using the standard model, with fixed environmental parameters including wind speed, solar radiation, and ambient temperature. (Without cooling). The photovoltaic module was oriented in the standard position perpendicular to the ground and was fabricated with nozzles utilizing a flow rate of 0.02 liters per second per square meter. The findings indicate that there was a discernible variation in the surface temperature of the PV module, with a temperature differential ranging from 8 to 24°C, between the conditions of cooling and non-cooling.

Elminshawy et al.[37] aimed to examine the performance of Photovoltaic (PV) modules with automatic cooling and surface cleaning in comparison to those without such features, through both experimental and numerical means. (Fig. 6).

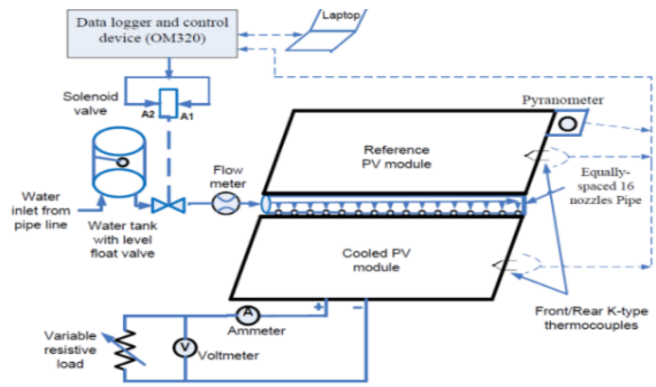


Figure 6. PV modules with proposed Schematic diagram. [37]

The findings indicate that the highest temperatures recorded on the front and rear surfaces of the reference module were 44 ◦C and 51 ◦C, respectively, while the ambient temperature remained constant at 29 ◦C throughout the day. The proposed cooling system yields corresponding temperatures of 24 ◦C and 31 ◦C. The aforementioned figures denote a decrease of 45.5% and 39% in the temperatures of the frontal and posterior surfaces of the module, respectively. The proposed cooling system has resulted in a maximum output power of 89.4W, whereas the reference module has a maximum output power of 68.4W. The module that underwent cooling and surface cleaning exhibits an efficiency of 11.7%, while the reference module lacking such arrangements only achieves 9% efficiency. The application of the proposed cooling technique results in a maximum open circuit voltage of 62.3V, whereas the reference module yields 59V.

The study conducted by Castanheira et al. [38] used a water spraying method for photovoltaic plants to optimize a closed-loop water cooling system with minimum costs and water usage. The findings indicated that it is feasible to enhance the annual PV output by 12% through the implementation of optimized water flow and ON/OFF cycles. This approach also resulted in a peak increase of 17%, which was achieved by reducing the PV temperature from approximately 60 °C to 30 °C, while incurring water losses ranging from 10 to 20 l/h.

Hasan and Aboaltabooq [39] used the CFD model to examine the impact of water temperature and flow rate on the efficiency of PV cells. The results showed that the use of a 2 mm nozzle diameter and 4 L.P.M water flow rates enhanced the efficiency of PV cells by 22.8%. Furthermore, the temperature of the PV panel decreased by 43.5% to 49.7% with the use of nozzle diameters of 5 to 2mm, respectively.

Hussein et al. [40] employed eight panels with plastic pipes to design a novel system to automatically cool photovoltaic (PV) panels by supplying water to them when their temperature exceeds a certain threshold. The initiation of water flow can be achieved through the activation of an electronic DC motor that is connected to a hosepipe, which is in turn linked to a water supply tank. A perforated pipe was used to extract undesirable heat from the front side of the PV panel by means of water dripping. The test recorded an increase in solar panel power by about 16.73% without the incorporation of a cooling system. The highest recorded improvement in solar panel power products, achieved on the second day, was 20.26% with the implementation of a cooling system.

Kamarudin et al. [41] developed a solar energy monitoring system using the Internet of Things IoT technology. The temperature sensor and intensity sensor were responsible for detecting the ambient temperature and light intensity, respectively. The sensory elements then transmit an alert signal to the microcontroller. At a temperature of 45°, the direct current pump was activated to start the cooling process. The results showed that the implementation of the cooling system has resulted in an increase in the mean voltage by 4.6%, an increase in the mean current by 12%, and in the mean output power by 17%.

To enhance the performance of photovoltaic modules, Haidar et al. [42] investigated the use of evaporative cooling by using two PV panels, one was fitted with a piece of cloth on the back surface. The water flows from a tank through rubber pipes attached to the panel's back surface, wetting the cloth. A significant decrease in photovoltaic panel temperature of over 20 ℃ was observed, resulting in an increase in electrical power generation efficiency ranging from 10 to 14% when compared to a reference PV panel.

In a recent study conducted by Muslim et al. [43], the impact of path location on the efficacy of water cooling chambers located at the rear of a photovoltaic module was investigated through experimental means; (See Fig. 7). The study involved the assessment of PV modules with and without cooling, utilizing two water flow styles (up-flow and down-flow) within modules. The modules were equipped with channels featuring three flow angles (60°, 30°, and 0°) to investigate the impact of flow style. The guides under examination were composed of 2mm-thick acrylic glass sheets. Based on the empirical findings, it was observed that Module I, which was characterized by a flow angle of 60°, exhibited a peak thermal efficiency of 80% when the flow rate was set at 4 l/min. Additionally, a notable enhancement of 54% was recorded across the flow rate range of 1-4 l/min. Under identical circumstances, it was observed that the electrical efficiency of cooling modules with a three-style angle increased by 17%, 15.3%, and 13.6%, respectively, when the flow rate in the cooling chamber was 4 liters per minute. In their study,

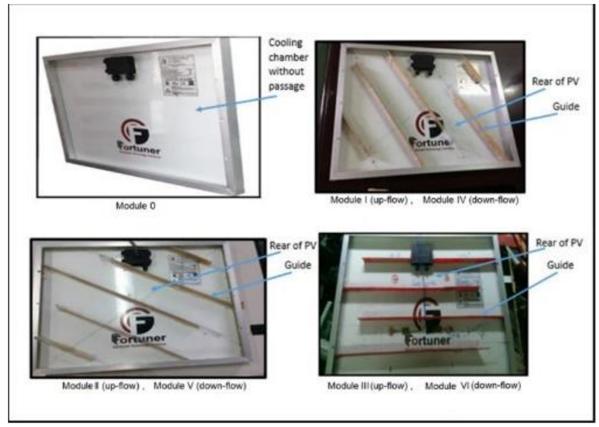


Figure 7. Experimental setup modules. [43]

Tarabsheh and Etier [44] conducted an analysis of the performance of photovoltaic modules, taking into consideration the varying operation temperatures of the cells within said modules. The photovoltaic modules were subjected to cooling through the utilization of a fluid that served a dual purpose as a collector of solar heat and a sink for heat dissipation. Additionally, the temperature distribution of each photovoltaic module was considered. The findings indicate that the incorporation of a cooling chamber via the lower module yields a significant enhancement in the performance of the photovoltaic module. The temperature of the module experienced a substantial decrease of roughly 20%, while the efficiency of the photovoltaic module demonstrated an increase of 9%. Bahaidarah et al.[45] Conducted a study utilizing both experimental and numerical methods to investigate the impact of circulation water within the cooling chamber on photovoltaic modules. A numerical model based on the engineering equation solver EES was developed, incorporating thermal and electrical modeling. In the event that the pressure surpasses the designated threshold, a bypass mechanism is activated to facilitate the pumping of water back into the reservoir, thereby ensuring that a safe level is maintained. The implementation of water-based active cooling results in a significant reduction of the functional temperature of the module, from 45 to 34 degrees Celsius, representing a decrease of 20%. Additionally, this cooling method leads to an increase in electrical efficiency of 9% (Fig. 8).

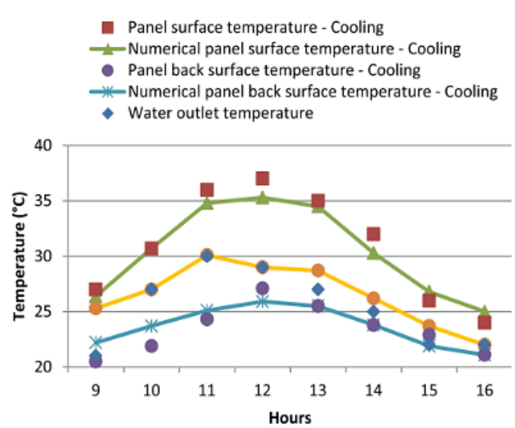


Figure 8. Comparison of numerical and experimental data for module surface[45]

Baloch et al. [46] conducted both experimental and numerical analyses on a converging channel heat exchanger for the purpose of cooling photovoltaic (PV) panels. The researchers used the principle of continuity to design the converging channel. The study focused on extreme environmental conditions in Saudi Arabia during the months of June and December and involved the CFD analyses of seven converging angles ranging from 0 to 10. The study determined that a converging angle of 2 yielded optimal temperature distribution and average cell temperature. Experimental evaluations were conducted during the months of June and December, and the performance parameters were compared to a developed model (see Fig. 9). Results showed a significant decrease in cell temperature from 71.2 C (non-cooled) to 45.1 C (cooled with converging channel) in June, and from 48.3 to 36.4 C in December. Additionally, the study found that the maximum improvement in power output was 35.5%, and the upgrade in conversion efficiency was 36.1% observed when compared to the non-cooled PV system.

Mustafa et al. [47] established a method to enable direct contact between the working fluid and the rear surface of the PV panel by using a collector composed of fiberglass sheets. To evaluate the PVT collector's thermal and electrical performances, experiments were conducted at ranging of solar simulators from 450 to 850 W/m^{2}each adjusting the flow rate between 1.4 and 3 l/min. The findings indicated that the fiberglass collector's design has the potential to enhance the output power and attain a thermal efficiency of a maximum of 72.98%. In addition, the experiments demonstrated that at a flow rate of 3 l/min and a solar radiation of 850 W/m2, the collector can achieve a temperature reduction from 73.31℃ to 54.2℃. At an irradiance level of 650 W/m2, the panel temperature of a typical photovoltaic (PV) system was recorded to be 67.67oC. However, this temperature was reduced by 34.43% to 50.34oC when the irradiance level dropped to 450 W/m2. The aforementioned PV system, which used fiberglass as a collector, exhibited a total efficiency of 82.68%, comprising an electrical efficiency of 9.7% and a thermal efficiency of 72.98%.

Rahman et al. [48] investigated the impact of water cooling chambers located at the rear of a photovoltaic (PV) module on its efficiency. A heat exchanger was employed on the back surface of the PV module to cool the cell temperature. Under an irradiation level of 1000 W/m^2 without cooling, the temperature of the cell rose to 56 C, resulting in a reduction of the output power to 20.47 W and a decrease in the electrical efficiency to 3.13%. A reduction in output power by approximately 0.37 W and a decline in electrical efficiency by 0.06% for every 1 C rise in temperature of the solar cell were recorded. The findings indicated that a rise in irradiation intensity by 100 W/m^2 resulted in a corresponding increase of 2.94 W in output power, accompanied by a 4.93 ℃ elevation in the temperature of the solar cell. The application of water cooling on a photovoltaic (PV) module resulted in a reduction of the module temperature to 22.4 ℃, with a cooling water flow rate of 80 L/h and an irradiation of 1000 W/m2. This reduction in temperature led to an increase in the output power by 8.04 W and an increase in the electrical efficiency by 1.23%. The output power and efficiency produced with cooling was 27.33% greater than that produced without cooling.

Hussien et al. [49] developed an experimental rig to assess the performance of photovoltaic/thermal systems (PV/T) using a proposed cooling technique. The cooling technique involved the implementation of a heat exchanger and water-circulating pipes situated at the rear surface of the PV module to mitigate the issue of high heat accumulation within the PV cells during operation. The findings showed that in the absence of active cooling, the PV module temperature was elevated, and the solar cells were only able to achieve a conversion efficiency of approximately 8%. Nevertheless, under the active water-cooling condition, the PV module exhibited a decrease in temperature to 76.8oC at a flow rate of 0.1L/s, 74.5oC at 0.2L/s, and 70.1oC at 0.3L/s. The decrease in temperature resulted in a corresponding increase in the efficiency of the solar panel, with values ranging from 8.6% to 9.6% depending on the water mass flow rate. Additionally, the thermal efficiency increased to 12.3%.

Salman et al., [50] A novel cooling system design has been proposed and subjected to numerical investigation. The utilization of water as a functional fluid within the posterior chamber of a photovoltaic panel is observed. Porous media is employed within the chamber to enhance the process of convection heat transfer. The ANSYS software is employed to simulate the steady-state flow of water, which is incompressible, by utilizing the Navier-Stokes equations. A reduction in the mean temperature of the module by approximately 9-14 ◦C was recorded as a result of the inclusion of the porous media. Moreover, the augmentation of the flow rate significantly amplifies the heat transfer.

Hachicha et al. [51] observed that the application of water on the front surface of photovoltaic (PV) panels is a more efficient method of cooling compared to the use of a cooling box installed at the back of the PV panels. The removal of impurities and dust from the surface of photovoltaic cells resulted in an increase in efficiency.

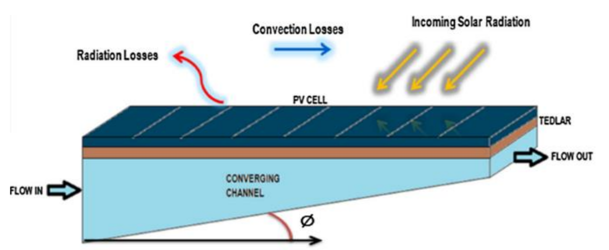


Figure 9. Schematic of converging channel heat exchanger with heat transfer modes. [46]

The results indicated that the implementation of back cooling leads to a reduction in the temperature of the photovoltaic (PV) cell by 1.7%, coupled with an increase in power output by 2.3%. Conversely, front cooling results in a decrease in temperature by 11.3%, while simultaneously increasing output power by 3.6%. When subjected to a cooling process that is increased by 18.3%, the temperature experiences a reduction of 7.7°C. The maximum power has experienced an annual increase of 5%.

The study conducted by Kadhim et al. [52] involved an experiment on the utilization of evaporative cooling for the purpose of cooling photovoltaic (PV) panels. The experimental setup consists of four distinct cases, namely Case (I) involving backside cooling, Case (II) involving front and back cooling with a pump supplying water every 35 minutes, and Case (III) involving cooling on both sides using an Arduino controller. The operation of the water-cooling pump is contingent upon the temperatures of the panel, as indicated by temperature sensors affixed to the front of said panel. This pertains to Case IV, which involves the replication of Case III while varying the rates of water flow. The experimental findings indicate that Case (I), (II), (III), and (IV) resulted in an average reduction of module temperatures by 4, 8, 12.2, and 12.6ºC, respectively, in comparison to a module that did not undergo cooling. The implementation of evaporative water cooling resulted in a significant enhancement in the conversion efficiency of the panel. Specifically, a total improvement of 1.74%, 2.8%, 15.8%, and 16% was observed in comparison to a non-cooling module.

Nižetić et al. [53] conducted a study on the development of a water-spraying method for cooling photovoltaic (PV) modules. The cooling behavior of the PV system was investigated using a cooling technique that involved the simultaneous supply of water on both sides of the PV panel. The findings of the experiment indicate that the implementation of the suggested cooling method during instances of maximum solar irradiation can result in a maximum overall enhancement of 16.3% in electric power output and a total increase of 14.1% in PV panel electrical efficiency. Furthermore, it was observed that the temperature of the panel was reduced from an average of 54°C in the absence of cooling to 24°C when both front and backside cooling of the PV panel were implemented.

3.2.2 Studies that to use of air as the working fluid in cooling

In a recent study by Alsayah [20], a novel solar energy system utilizing air guide technology was developed. The system operates by pulling air from the bottom up, as the density of hot air is low and thus directed upwards. This air-cooled photovoltaic system represents a cost-effective and contemporary approach to cooling PV cells, thereby reducing the temperature of the cell base and enhancing the performance and efficiency of the PV cell. The study presents experimental and theoretical findings on the cooling of a photovoltaic (PV) cell using an air guide system. The results indicate that the highest reduction in temperature of the PV base was 37.22%, achieved by reducing the temperature of the cell's base by 22.622 °C from 70.622 °C to 48°C at an airflow rate of 0.049 kg/s. Additionally, the study reports a 14.88% increase in the maximum power of the PV cell after the cooling process and a net electric power added to the production of the PV cell of 42.3 watts. The temperature difference between the air outlet and the air inlet temperature was found to be 13.717 °C.

Mojumder et al. [54] developed a system using air pull flow and thin rectangular fins to cool a photovoltaic panel. The study conducted experimental measurements of the average temperatures of various surfaces, including the top and rear PV surfaces, the collector back wall surface, and the collector inlet and outlet temperatures. These measurements were taken under different conditions, including varying fin numbers (ranging from 0 to 4), mass flow rates (ranging from 0.02 kg/s to 0.14 kg/s), and solar radiations (ranging from 200W/m2 to 700W/m2). The aforementioned readings were utilized in the computation of the thermal and electrical efficacy of the proposed photovoltaic/thermal system. The results indicate that when employing four fins at a mass flow rate of 0.14 kg/s and a solar radiation intensity of 700W/m2, the maximum thermal efficiency and PV efficiency achieved were approximately 56.19% and 13.75%, respectively. The performance of PV is significantly impacted by the air mass flow rates and the quantity of fins.

Jaffar et al. [55] chose a centrifugal fan, capable of achieving a maximum volumetric flow rate of 760 m^3/h, to extract air through the duct. The device underwent modifications to enable operation at three distinct velocities, namely 1.5, 2.5, and 3.5 meters per second. These velocities correspond to specific air volume flow rates, which are 335, 540, and 760 cubic meters per hour, respectively. The reference photovoltaic (PV) module attained a maximum back temperature of approximately 69 °C. The results analysis indicated that the photovoltaic-thermal (PVT) technique can reduce the PV temperature by 5 to 16 °C, contingent upon the alteration of air volume flow rate from 335 to 760 m3/h. By contrast, the highest increase in PVT power was observed to be 8.2% when the maximum air volume flow rate reached 760 m3/h, resulting in an electrical efficiency of approximately 17.9%.

Saygin et al. [56] proposed a model wherein the photovoltaic (PV) panel is positioned within the collector, as opposed to being placed on an absorber plate (see Fig. 10). The ingress of air into the system occurs via a rectangular aperture located at the central region of the glass cover. The air subsequently traverses both above and below the panel before egressing through a second aperture situated at the posterior aspect of the collector. The experimental parameters were adjusted to vary the distance between the panel and the cover, as well as the air mass flow rate. The optimal thermal performance was achieved at a distance of 3 cm between the photovoltaic module and the cover. Regarding electrical efficiency, the maximum value was achieved at a distance of 5 cm and a flow rate of 0.021 kg/s between the cover and the panel. It was recorded that the distance separating the PV panel and cover is the primary factor of significance. Additionally, there exists a noteworthy interaction between the distance and mass flow rate. The PV/T collector exhibited an average electrical efficiency of 7.7% when the distance between the panel and cover was 5 cm, whereas the PV modules demonstrated an average electrical efficiency of 6.9%.

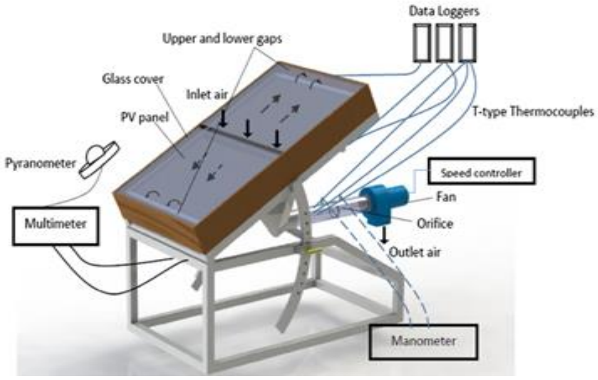


Figure 10. Schematic diagram of experimental set-up [56]

Bambrook and Sproul [57] evaluated the efficacy of a photovoltaic thermal air collector through experiments. A distinctive discovery was reported, in which the supplementary electrical photovoltaic output surpassed the fan energy demand for air mass flow rates that varied between 0.03 and 0.05 kg/s m^2. The results of the experiment indicated that the PVT air system demonstrated a rise in thermal and electrical PV efficiencies as the air mass flow rate increased. The study found that the thermal efficiencies varied between 28% and 55%, whereas the electrical photovoltaic efficiencies were observed to be in the range of 10.6% to 12.2% during midday.

Zhao et al. [58] affixed the cooling fin for heat dissipation directly onto the back of the solar panel and coated it with an insulating layer to facilitate the creation of an air-cooling channel. The experimental conditions include a constant mass flow rate of air at 0.011 kg/s, three varying numbers of fins (0, 5, and 10), and different levels of solar irradiance ranging from 200 W/m2 to 600 W/m^2. Upon comparing the median electrical efficiency of the three distinct types of fins under varying solar irradiation, it has been ascertained that the electric efficiency value of all three types of fins is approximately 16%, with a negligible difference of less than 0.6%. The median comparison of photoelectric photothermal comprehensive efficiency revealed that the comprehensive efficiency of five groups of fins and ten groups of fins was 61.08% and 69.85%, respectively. The study reveals that the utilization efficiency of 5 groups of fins is 61.08%, exhibiting a marginal improvement of 8.77% compared to the utilization efficiency of 10 groups of fins. This outcome suggests that the arrangement of fins has a favorable impact on the PV/T system.

This study proposes an active cooling technique for photovoltaic (PV) panels based on the rate of distribution of fluid flow. Amelia et al., [59] The present study presents a comparative analysis between a photovoltaic module equipped with a direct current fan and one without. Furthermore, it should be noted that the DC fan mandated for this system will not be in continuous operation for a full 24-hour period. Rather, it will solely function during specific instances of certified photovoltaic operating temperature. For the purposes of this study, all DC fans utilized will be activated once the operational photovoltaic temperature surpasses 35°C. Experimental findings indicate that the maximum temperature of the PV panel was recorded at approximately 59.88 °C in the absence of cooling. However, the Implementation of four DC fans resulted in a reduction in the average temperature of the PV panel. The average has increased by 22.22%. At a temperature of 35.28°C, the maximum power output of a photovoltaic (PV) panel can be increased by 44.34% through the utilization of four operational units, resulting in a current production of 4.97 A.

Farhana and colleagues [60] designed, fabricated and conducted experimental investigations on a solar system. The cooling system for this solar module utilizes DC fans and aluminum sheets as a means of dissipating heat. A comparison between the two systems reveals that the implementation of a cooling system results in a maximum reduction of 12°C or 40% in the temperature of the solar module. The results indicate that the temperature of the module experiences a 1.6 °C increase for every 100 W/m2 rise in solar irradiation when an active cooling system is employed. In the absence of active cooling, the temperature will increase by 1.8 °C per 100 W/m2.

The study conducted by Deokar et al. [61] presents a novel active cooling system that utilizes thermal grease and Metal sheet chips to efficiently cool photovoltaic (PV) panels. The proposed system boasts a weight of only 0.75 kg/m2, which is notably lighter than aluminum fins. Furthermore, the heat that is rejected during the cooling process of the PV panel is repurposed for solar thermal drying. The results of the proposed active cooling system, which utilizes thermal grease and metal sheet chips, demonstrated promise at an air velocity of 5.2 m/s. This study examines the electrical efficiency, drying time, and overall system efficiency through experimentation. The results indicate that the maximum temperature at the rear surface of the PV panel was 55.4 ℃ and 71.5 ℃ for the cooled and non-cooled panels, respectively. The cooled PV panel demonstrated an average voltage and electrical efficiency improvement of 4.0% and 12.3%, respectively, compared to the non-cooled PV panel. The operational temperature of the photovoltaic cell was lowered by 16.1 ℃ in the cooled panel as compared to the non-cooled panel.

Maghrabie et al. [62] investigated the efficacy of an air-cooling system affixed to the rear surface of a photovoltaic (PV) cell in enhancing its performance. The empirical findings indicated that this led to a reduction in the mean surface temperature of the photovoltaic (PV) cell on the back surface of the PV cell by 11%; and on the front surface by 10%. The implementation of a cooling system has resulted in a 4.4% improvement in the electrical power output and a 3.7% improvement in the electrical efficiency of the PV cell, as compared to the performance of the PV cell without a cooling system.

Abdallah et al. [63] investigated four cooling methods which are perforated-ribs-heat sink under natural convection (PRNC), phase change materials (PCM), galvanized duct with forced convection (GDFC), and ducted fins under forced convection (FDFC). The results indicated that the average percentage improvement in second law efficiency was 0%, 33%, 53%, and 72% for the PCM, PRNC, GDFC, and FDFC, respectively, compared to the control PV module without any cooling technique. The findings of the study indicate that the integration of FDFC with the PV panel results in a more consistent and reduced temperature, with an average of 39 ◦C.

Elminshawy et al. [64] proposed a new cooling system for photovoltaic (PV) panels that uses an earth-to-air heat exchanger (EAHE) to pre-cool the ambient air. The implementation of geothermal pre-cooled airflow over the back surface of a PV module at an optimal rate of 0.0288 m3/s resulted in a reduction of the average temperature of the PV module from 55°C to 42°C. As a result of the reduction in photovoltaic (PV) module temperature, there was an observed increase in the average output power and electrical efficiency of the PV module by approximately 18.90% and 22.98%, respectively.

Mazón-Hernández [65] investigated the effects of the free and forced convection of air using different shapes of ducts (0.105, 0.135, 0.165 m) on the electrical characteristics of a PV module. In order to achieve the intended objective, a pair of photovoltaic panels were employed, with one of the panels serving as a control and the other panel featuring an air channel beneath it that varied in spatial dimensions. The electrical output of a panel subjected to forced convection cooling is comparatively greater than the output achieved through free convection. The electrical power output of a photovoltaic (PV) panel that is cooled by forced convection is observed to be 3-5% higher than that of a panel cooled by natural convection, for a given aspect ratio. This improvement in power output is found to be directly proportional to the velocity of the forced airflow within the duct, for various fan-induced velocities (2, 3, and 4 m/s). The observed increase in electrical power output is attributed to the reduction in temperature of the PV panel, which is found to be in the range of 10-16 degrees Celsius. Upon comparing the two instances of forced convection, it was observed that there was a 2.4% increase in power and the temperature of the panel was lowered by 7∘C at a higher forced velocity. Teo et al. [66] From the experiment result, it shows the effect of using the active cooling mechanism. Under the situation where no cooling was used, the operating temperature of the PV module attained a value as high as 68 ℃ and the electrical efficiency dropped significantly to 8.6%. By using the blower to cool the PV module with Fins fitted in the duct to increase the heat transfer rate, the operating temperature of the module could be maintained at 38 ℃ and the electrical efficiency could also be kept at around 12.5%. Besides, an optimum flow rate was also found in this study. The airflow rate of 0.055 kg/s is sufficient to absorb the maximum amount of heat from the PV module.

This experimental investigation aimed to Enhance the electrical performance of solar panels in hybrid systems can be achieved through the implementation of two working fluids that incorporate active cooling and self-cleaning techniques in a simultaneous manner. The novel hybrid system was subjected to active cooling on its Rear side through forced air circulation, while its front side was subjected to cooling and cleansing through the flow of water.

The study conducted by Lebbi et al. [67] involved the development and execution of an experiment for a novel hybrid system. The system was subjected to active cooling from the rear of the photovoltaic (PV) module through forced air circulation, while the front side was cooled and cleansed by flowing water. (Fig. 11).

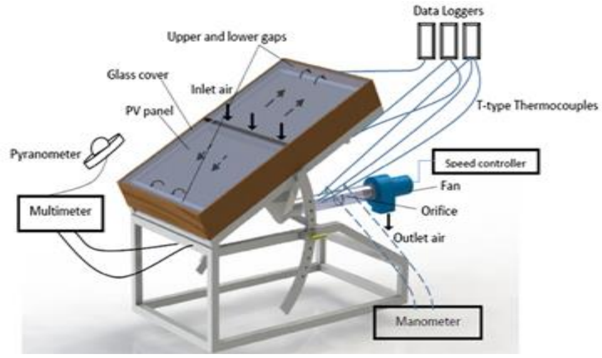


Figure 12. Schematic diagram of experimental set-up[59]

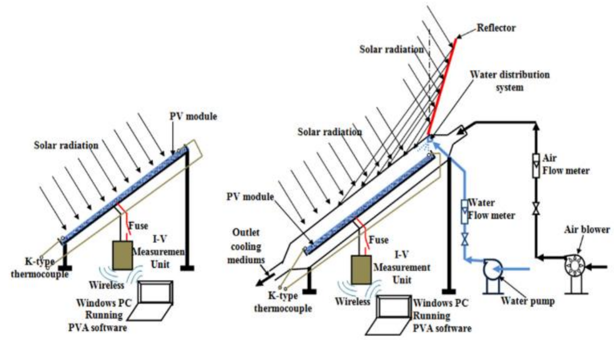


Figure 11. Schematic diagram of the conventional PV module and the PV module with a reflector and cooling techniques[68]

The empirical findings indicate a negative linear correlation between the electrical efficiency and the rise in temperature of the photovoltaic module, specifically in the reference scenario where cooling was not employed. The PV module installed in the new hybrid system exhibited an average temperature reduction of 15°C in comparison to the reference case. Under equivalent operational circumstances, and during the zenith of worldwide solar radiation, specifically. The results indicate that the electrical efficiency of the system improved by approximately 5.7% compared to the reference case, with an increase in output voltage and electrical current of 9.22% and 6.19%, respectively. The new hybrid system demonstrated a gain of up to 13.17% in electrical power output compared to the reference case. Additionally, the hybrid PV/T Bi-fluid system exhibited an overall energy efficiency of 85.3%, with an average exergy efficiency of 14.7%.

4. Challenges and Future Outline

With the substantial effects of heat on the Electrical efficiency of PV, a great deal of effort was undertaken to identify cost-effective ways of cooling PV modules [68]. Below is a list of the challenges of developing a cost-effective PV cooling system.

1. It needs to recognize and understand the various variables affecting cell temperature and how potential cooling systems would be affected. It is important to design a

system depending on multiple factors, such as module orientation, location, and cooling system components

2. The high surface area to cool with due consideration to the extremely low power output per module.

- Balancing the greater initial cost with higher performance. Therefore, any effective cooling system must be extremely inexpensive as it does not drive the cost of the system upward significantly.
- If a system is designed without considering environmental influences, the device maintenance costs could outweigh the benefits of improved power output.
- Work on the analysis of many photovoltaic technologies, ranging from silicon to thin films, multi-junction systems, and solar concentrating. This is to identify improvements and innovations needed for further expansion.

photovoltaic is one of the fastest growing industries worldwide and in order to maintain this growth rate need for new developments with respect to material use and consumption, device design, reliability, and production technologies as well as new concepts to increase overall efficiency. The study suggests that future research should focus on the economic and environmental impact of cooling systems to develop practical sustainable PV systems and reduce research gaps. If a cooling system is to be successful in maximizing the cooling, these challenges must be addressed while designing a PV cooling system.

5. Conclusion

This paper presents a comprehensive review of active cooling techniques for photovoltaic (PV) panels that aim to improve their electrical efficiency. The most important conclusion reached through the following can be stated the power generated by photovoltaic panels decreases with increasing operating temperature, which makes cooling techniques necessary. Cooling methods are generally divided into active and passive. Active cooling methods, which provide high-performance heat transfer and improved cooling rates, are preferred over passive technologies. Uses water and air as common fluids for the active cooling process in the cell, and hybrid PV/T systems can be used to improve and control the PV panel temperature, improve energy conversion efficiency, and reduce space requirements. Water cooling with channels below the photovoltaic unit is the most effective method among the active cooling methods, but freezing may limit its use during cold seasons. Forced circulation of fluids is more efficient than air in active cooling, but it requires higher pumping power and thus requires higher energy than using air. One of the disadvantages of active cooling is that it needs an electric power source that may be external or from the electrical panel itself. Active cooling also needs large areas and may hinder the solar tracking devices that are used in solar panels. The process of obtaining water is one of the challenges facing the use of active water-cooling technology, unlike the use of available air, but it is less efficient in cooling. Finally, it is noted that despite the many studies that dealt with the issue of active cooling, most of them are research or experimental studies that did not rise to the actual application of cooling large areas of solar cells to find out their most prominent negatives in the long term.

The study suggests that future research should focus on the economic and environmental impact of cooling systems to develop practical sustainable PV systems and reduce research gaps.

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Abbreviations

PV	Photovoltaic
η	efficiency
ηEl	electrical efficiency
PCM	phase change material
PVT	photovoltaic thermal
Q	volumetric flow rate
wt%	by weight concentration

Conflict of Interest

The authors state that there are no conflicting interests involved.

Author Contribution Statement

Authors Muna S. Kassim and Raid A. Mohamed: proposed the research problem.

Author Abdullah M. Al-Sadoon: verified the analytical methods investigated [cooling active method] and supervised the findings of this work.

Both authors discussed the results and contributed to the final manuscript.

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