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Cooling techniques for cutting-edge photovoltaic modules

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Abstract: The overall efficiency of solar systems, specifically photovoltaic panels, is typically inadequate. The power generation module's output is significantly impacted by the increase in temperature at its surface. This increase is attributable to the conversion of ingested sunlight into heat, which diminishes the panel's performance, energy efficiency, power output, and lifespan. Implementing cooling techniques may present a viable resolution for mitigating the risk of PV panels overheating and for decreasing cell temperature. This article describes in depth a variety of viable cooling techniques, including innovative and cutting-edge solutions for photovoltaic panels, and forecasts future research directions. This article presents various cooling techniques and their capabilities in order to provide researchers with a deeper understanding and useful guidelines when attempting to investigate, enhance, or optimize cooling methods for PV modules.

Keywords: PV-Photo Voltaic, PCM-Phase Change Materials, TEG – Thermo Electric Generator

I. INTRODUCTION

Individuals inhabit a consumer-driven and energy-intensive environment in this industrialized world. This has played a role in the expeditious depletion of fossil fuels, the principal inputs in the generation of electricity. Hence, the exploration of sustainable energy sources has become an imperative task to mitigate our dependen ce on fossil fuels. Globally, solar energy is the most widely utilized non-conventional energy source. All forms of renewable energy derive from solar radiation. It is capable of being converted either directly or indirectly into electrical energy via thermal collectors or photovoltaic (PV) systems. The efficiencies of solar thermal systems vary from 40% to 60%, whereas photovoltaic systems exhibit efficiencies ranging from 10% to 20% . In order to produce electricity, solar cells exclusively utilize the visible spectrum spanning from 380 to 700 nanometers. Energy levels beyond 700 nanometers are inadequate for the formation of electron-hole pairs. Although shorter wavelengths of radiation, such as X-rays, possess high photon energies, the ionisation processes of these photons could potentially cause injury to the photovoltaic cell. When directed beyond the visible spectrum, the solar cell's undesirable radiant energies are converted to heat, resulting in an increase in temperature.

A reduction in the operational temperature of the solar cells results in an augmentation of their electrical power [5–7]. Furthermore, further improvement will be observed in the overall quantity of electricity generated if the lifetime of photo voltaic is extended. The assertion that the efficiency of photovoltaic (PV) panels is substantially influenced by the material band gap and the wavelength of the sunlight is widespread. An approach to enhancing performance involves the exploration of innovative materials for the construction of efficient solar systems. Solar photovoltaic (PV) efficiency significantly diminishes as the temperature of the solar cells rises. Approximately 5–20% of the incident solar radiation that reaches the solar cell surface is converted into electrical energy. The remainder of the radiation is absorbed by the cell as heat or transmitted in the opposite direction. As a result of the heat absorption, its temperature rises to 70 degrees Celsius. Numerous studies have been conducted to determine how to cool photovoltaic panels so as to increase their efficacy.

This study provides an overview of the principal characteristics of the numerous cooling methods. The research is structured into the following five sections. Section 1 provides a concise overview of the subject matter. In Section 2, the environmental parameters that affect the efficacy of the module are discussed. In Section 3, the various methods for cooling photovoltaic panels in order to increase their efficacy are described. The issues and obstacles encountered during the development of refrigeration techniques are discussed in Section 4. Future implications and conclusions comprise the concluding section.

II. ENVIRONMENTAL FACTORS THAT INFLUENCE MODULE PERFORMANCE

A multitude of environmental parameters exert an influence on the solar panel. For instance, the installation height, sunlight, ambient and module surface temperature, wind speed, humidity, shading, and dust. Critical factors in this context are, without a doubt, solar irradiance and temperature.

2.1. The Impact of Solar Radiation

The short circuit (ISC) current is proportional to the light intensity due to the fact that it is influenced by the number of photons absorbed by the semiconductor material. Consequently, the conversion efficiency remains relatively stable, such that the power output is typically proportional to the irradiance; however, as the cell temperature increases, the efficiency diminishes (see Figure 1). The open-circuit voltage (V_{OC}) exhibits minimal variation in response to changes in light intensity.

2.2. The impact of surrounding climate

As the temperature of the panel exceeds 25°C, there is a significant decrease in the VOC. However, the increase in short-circuit current, denoted as Isc, is only marginal (see Figure 2). The temperature coefficient denotes the impact of temperature on photovoltaic performance. Temperature increase leads to a decrease in power output as a consequence. The percentage of temperature coefficient signifies a variation in output when the temperature deviates from the standard 25°C. To illustrate, a 0.5% increase in temperature will result in a 0.5% decrease in the maximal power output of a particular panel.

Table 1 provides specifications for the nominal operating cell temperature (NOCT) and standard test conditions (STC). On sunny days, however, the maximum panel temperature in the equatorial region is 70 degrees Celsius. This level of extreme temperature generates a localized hotspot and weak currents. Therefore, exceeding a panel temperature of 45°C results in a reduction in both electrical performance and panel lifespan. The response of various solar cell technologies to temperature variations varies, and this response variation has been the subject of extensive research in the scientific literature (Table 2). Temperature-dependent degradation of photovoltaic (PV) electrical efficiency is another significant area of study for which the literature provides numerous solutions. The widely recognized equation is as follows: $\eta = \eta_r [1 - \beta (T_m - T_r)$. The value of β is approximately 0.004 K. The efficacy of this system is computed under anSTCconditionof25°C. Therefore, it is critical to employ suitable cooling techniques to extract heat from the photovoltaic (PV) system, thereby mitigating the adverse effects of cell temperature and regulating the operational temperature to the manufacturer-specified range. The heat equilibrium that is characteristic of the deployed solar PV is illustrated in Figure3. The heat balance of the solar module reveals that convective heat loss, which occurs as a result of airflow over the module's surface, accounts for approximately 66% of the over all heat loss (Table3). The confluence of elevated irradiance and temperature leads to the panel becoming overheated, potentially resulting in the following:

- The decrease in performance.
- The decrease in conversion efficiency.
- Increase cell degradation.
- Reduce the life of the cell.

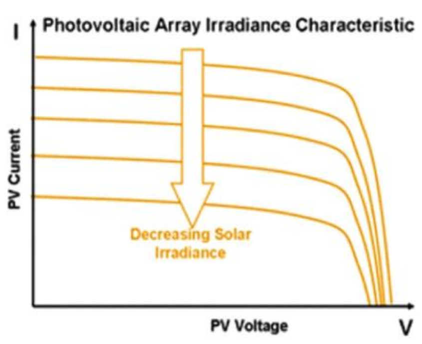


Fig.1 Solar P-V characteristics: the influence of solar irradiance.

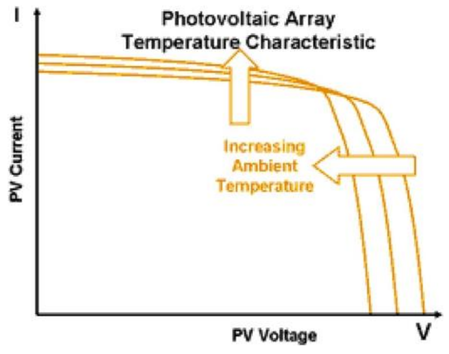


Fig. 2 Illustrates the attributes of a solar Photo voltaic system, focusing on the impact of temperature

TABLE 1 STC and NOCT conditions of a Solar Photovolatic module

Parameters	STC	NOCT
Solar radiation (W/m^2)	1000	800
Ambient Temperature (C)	25	20
Air mass	1.5	-
Wind Speed	-	1
Module temperature (� C)	25	45

TABLE 2 PV Technology for various materials

P·V. technology	Material Thickness (�µm)	η_{ref} (%)	βref (�C^{-1})	Surface area required for 1kWp system(m^2)
Mono-cSi	200	16–24	0.0041	~7
Poly-cSi	160	14–18	0.004	~8
a-Si	1	4–10	0.011	~15
CIGS	~2	7–12	0.0048	~10
CdTe	~1–3	10–11	0.00035	~10

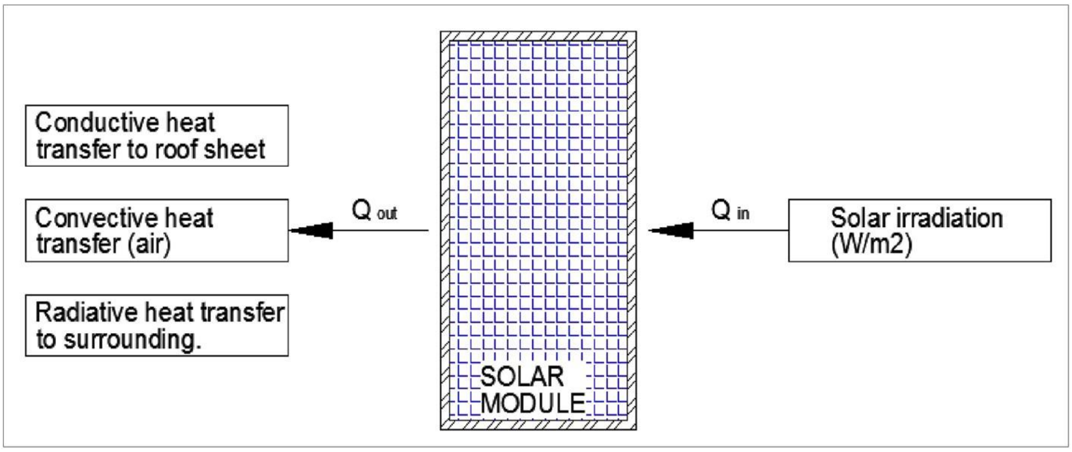


Fig. 3 The panel's heat balance.

Table 3 Heat loss from P·V. module.

S.No	Heat loss from module	Percentage
1	Conduction through mounting	2
2	Convection from top surface	42
3	Convection from bottom surface	24
4	Radiation from top surface	21
5	Radiation from bottom surface	11

2.3 Impact of shading and particles

In addition to the ambient temperature and climatic conditions, the temperature of photovoltaic (PV) modules also rises due to direct and indirect partial shading issues; a number of recent studies are pertinent to our current investigation.

The shading on the photovoltaic module may be the result of dust deposition (for instance, if this deposition is uniform across the module, it may indicate a thermal runaway on the PV panel) or the projection of the shadow of an object positioned at a considerable distance from the solar panel (for instance, a tree or a candelabrum of lighting, etc.). Similarly, hot areas may form on the PV module when partial. Partial shading and hot regions have the potential to cause power loss exceeding 70% . Dust is classified as pulverized particles with a diameter not exceeding 500 µm. Soiling, the second environmental parameter, is determined by the size and density of the material as well as its distribution (uniform or partial) on the PV module. The efficacy reduction is contingent upon the precise mass and dimensions of the dust particles that accumulate on the surface. with regard to the PV module. The process of particle deposition on the photovoltaic surface is significantly accelerated in arid climates. An approximate 40% reduction in solar output is attributed to dust particles.

2.4 Consequences of humidity

Humidity refers to the proportion of water that is present in the atmosphere. Frequent usage of the relative humidity to denote air humidity, or the quantity of moisture in the air. In order to assess the impact of precipitation, two conditions are typically taken into account, according to a number of researchers. Initially, the impact of water vapor particles on solar irradiance; subsequently, the influence of humidity levels upon entry into enclosed photovoltaic modules. In proportion to the fluctuations in daily temperature, the relative humidity also undergoes corresponding modifications. There exists an inverse correlation between temperature and humidity.

2.5. The Impact of Wind

Advocating for the direct correlation between wind velocity and solar PV efficiency may not be an entirely accurate notion. However, it contributes significantly to PV generation. In essence, solar cell temperature decreases when wind flows . The wind's cooling effect on the solar panels reduces electron vibration, thereby enabling the electrons to transport more energy as they ascend to the upper state. PV systems chilled by 1 degree Celsius are 0.05% more efficient.

III. SOLAR PHOTOVOLTAIC COOLING METHODS

3.1 Perquisite for refrigeration

Surface temperature fluctuations are subject to the impact of external climatic factors, including but not limited to atmospheric temperature, moisture, wind speed, and concentrated dust. An increase in efficiency can be achieved through a reduction in the operating temperature, given that adjusting other parameters becomes more challenging. In the context of installing photovoltaic panels on building facades, which are oriented vertically and lack a discernible direction, solar radiation represents an uncontrollable factor. In an effort to increase the efficiency of photo voltaic by mitigating the problem of temperature rise, numerous cooling techniques have been implemented and evaluated in a wide range of scholarly works.

3.2. Categorization of cooling methodologies

In an effort to decrease the operational temperatures of solar cells, researchers are developing active and passive cooling systems. Optimal cooling of the photovoltaic array has been observed to decrease output loss and enhance the dependability of the photovoltaic module. Passive and active cooling techniques are utilized to enhance the functionality of PV modules. Active cooling necessitates a coolant, such as water or air, and typically requires the use of a fan or pump. Passive cooling eliminates the need for additional power to chill photovoltaic cells. To regulate and sustain the operational temperature, considerable investigation was conducted regarding the application of liquid coolant, air, and various other liquids, frequently water or glycols. An essential economic consideration is whether or not increased power output via active cooling will compensate for increased power consumption. Conductive cooling, air passive cooling, and water passive cooling are the three primary classifications of passive cooling techniques. Passive cooling may involve the addition of heat pipes, sinks, or exchangers to facilitate natural convection cooling . The material used for the heat sinks was in fact highly thermally conductive. In order to facilitate the transmission of heat from the solar panel to the surrounding environment, they are positioned at the lower section. Consequently, passive cooling technologies are deemed efficacious in mitigating the temperature of photovoltaic cells due to their comparatively uncomplicated and economical manufacturing processes. Over time, cooling technologies have progressed towards increasingly intricate methods, incorporating heat sinks, micro channels, heat exchangers, phase-change materials (PCMs), nano-fluids, thermoelectric generators (TEGs), and systemic combinations thereof.

Beam splitting (or spectrum filter) technology, which differentiates the wavelengths utilized for photovoltaic (PV) cells from those utilized for the thermal conversion of the PVT system, pertains to the innovative and specialized field. The various methods of chilling are illustrated in Figure4.

3.3 Air-dependent refrigeration

Air-based passive methods for chilling photovoltaic panels and balancing systems are implemented naturally and without the use of mechanical equipment. Natural convection remains a widely utilized method for cooling photovoltaic modules owing to its straightforwardness, minimal cost, and absence of material additions. By means of convection, heat is removed from photovoltaic panels when air flows over them; this air is more efficient than air flowing beneath the panels. As previously stated, active air-conditioning is the most fundamental form of cooling. Active air-cooling systems generate circulation through the use of fans or other mechanisms. It is possible to construct such systems in a way that takes advantage of the surplus heat produced by the solar panels. Thus, the cooling of photovoltaic panels can be improved by affixing metallic materials featuring vents to the reverse surface of the panels in order to facilitate significantly increased air circulation. By creating an air opening between the walls and the photovoltaic system, it is possible to regulate the temperature of the system below 40 �C. Under photovoltaic panels, forced ventilation strategies include open-air channels, metal frames, fins, and ducts. Teo et al. significantly reduce the temperature of solar panels and increase their efficacy by 12 to 14% through the use of array ducts. Mazon-Hernandez investigated forced convection cooling by employing fans to cool the reverse side of photo voltaic modules affixed on the roof (Figure5). An observed decrease of 15 ^{0}C in the maximal cell temperature accompanied by a 2% increase in overall efficiency was documented. It has been demonstrated that the distance between the module and the roof, the air mass flow rate, and the local ambient temperature have a more significant influence on the photovoltaic performance. Photovoltaic systems do not employ active air conditioning because they are typically situated in open air. The airflow between panels is significantly influencing the cooling of the panels and the overall balance of the system.

3.4. Cooling by liquid

Continuous water flow is required for the refrigeration system; this requires additional pumping energy and involves cumbersome methods. In all of these systems, water circulation can be managed through the utilization of solar-powered DC pumps integrated into active refrigeration technology. A multitude of water active cooling technologies have been the subject of research. In this section, we will highlight several effective methods, along with their primary characteristics.

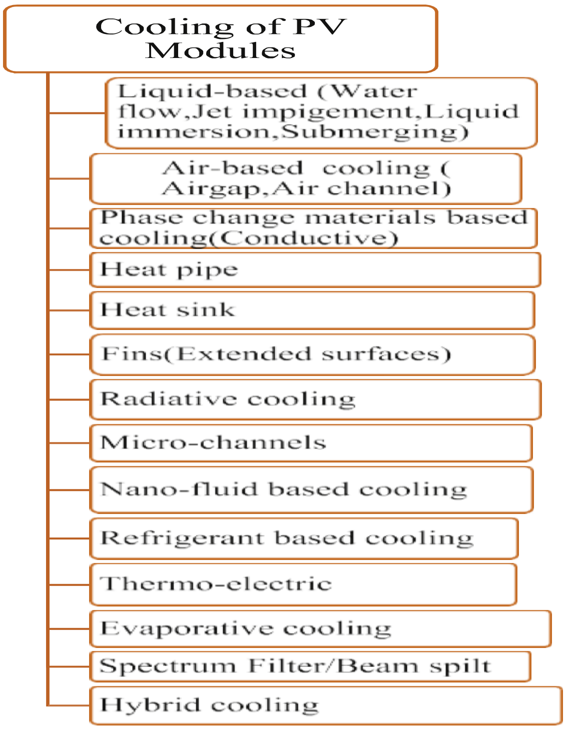


Fig. 4 Cooling technology classification.

Fig. 5 Illustration of forced and natural Convection air cooling

3.4.1 Forced circulation of water

The implementation of heat pipelines on the reverse side of module panels can effectively reduce temperature, even when liquid is employed as the cooling medium for the cells. The excess radiation absorption waste heat from photovoltaic modules can be transferred to the circulating coolant or utilized for alternative purposes. According to research (Wu 2011), the heat transfer capacity of the pipe material has a significant impact on the overall efficacy of the system. However, due to the high material and installation costs associated with the forced water circulation cooling procedure, it is not a viable option for large-scale solar plants.

3.4.2. Cooling by liquid immersion

By employing an immersion cooling method, photovoltaic modules are submerged. Results of increased efficacy are achieved via the heat absorption of water by photovoltaic panels. The module's efficacy can be enhanced through submersion in water. As illustrated in Figure 7, Mehrotra et al. demonstrate that an increase in electrical efficacy of 17.8% is achievable at a depth of 1 cm. Although immersion cooling has the potential to significantly reduce temperatures and has minimal environmental impact, it is not suitable for floating solar systems.

3.4.3 Spraying water

In this system, water is discharged via the sprinklers located in front of the PV modules, which are connected to the pump and pipelines (see Figure 6). Intriguing findings from prior research on water spraying indicate that electrical efficacy can increase by as much as 15 percent in environments with severe weather. Although substantial water is consumed and squandered by this system when installed on the overland PV plant, it may prove to be a viable and economical alternative for floating solar systems. The scientific evaluation of water spray on both surfaces of the PV panel performance was conducted by Nizetic et al. [23]. According to the findings, front-side cooling produces superior results in comparison to back-side cooling. The realized electrical power enhancement amounted to around 14.6%. For the purpose of cooling solar panels, Moharram et al. developed a water discharge technique. PV modules, a storage canister, a pump, spray nozzles, and a recycling system are all components of the apparatus. By employing water discharge,the temperature of the solar panels is decreased to 35^0C.

3.5. Conductive phase change material

Cooling via phase change materials (PCM) is an example of a unique type of passive conductive cooling. PCMs are thermally competent substances that enable the stabilization of temperature. Significant amounts of so-called "latent" heat are absorbed or released when these substances undergo a change in state, as in the case of the thawing and freezing cycle. Organic oil, inorganic salt hydrates, and eutectics are all components of PCM. Two factors—melting temperature and latent heat—are utilized to determine the proper PCM (Figure 8). Although this does not strictly qualify as passive cooling, it does not necessitate additional exertion and heat is dissipated more efficiently, resulting in temperature maintenance. In fact, integrating PCM with the PV module would make it a superior alternative (Figure. 9) on account of its critical characteristics, including diurnal heat absorption and nighttime release.Superior latent heat; substantial absorbing capacity prior to solidification or melting; temperature stability during phase transitions; marginally elevated melting point. For instance, PCMs containing salt may cause corrosion when exposed to metal, whereas paraffin may react with plastics. In relation to temperature, it is critical that the PCM has a melting point higher than the ambient temperature at which it functions. If the PCM's melting point is lower than that of the environment, it will initiate liquefaction prior to the panel undergoing heating, thereby destroying its functionality. Paraben and other organic PCMs are extensively employed in thermal storage systems. Nevertheless, numerous studies have established that the low thermal conductivity of organic hydrocarbon structures hinders the rate at which heat is charged and discharged during the processes of melting and solidification. As a consequence of their greater phase change enthalpy, inorganic PCMs possess superior thermal properties. A particular phase change material (PCM) known as the CaCl2−6H2O – Fe3Cl2−6H2O eutectic can be employed to regulate the temperature and facilitate the cooling of PV panels.

3.6. Pipe heat

A heat pipe is a type of passive cooling apparatus that utilizes the processes of fluid evaporation and condensation within a sealed system to transfer energy from the source to the drain. A heat pipe, which is commonly found in systems with high thermal conductivity materials like copper or aluminum, is a sealed conduit that connects the evaporator and condenser. In Figures 10 and 11, a schematic and model of a heat conduit with a solar panel are illustrated.By converting heat from the solar panel to air or water, the heat pipe can decrease the panel's temperature and increase its efficacy. When the thermal contact resistance between the heat conduit and the solar panel is high, heat transfer performance is diminished in specific circumstances. A novel solid solar panel contact micro heat pipe array with a flat shape was devised by Zhao et al. The experimental investigation of a heat pipe array for photovoltaic (PV) cooling via air and water circulation was conducted by Tang et al.When air-cooling solar panels are utilized as opposed to conventional ones, the temperature falls by 4.7 شC and the power output increases by 8.4%. When water-cooling solar panels are employed, the temperature falls by 8^0C and the power output increases by 13.9%.A synopsis of several studies pertaining to heat pipes is displayed.

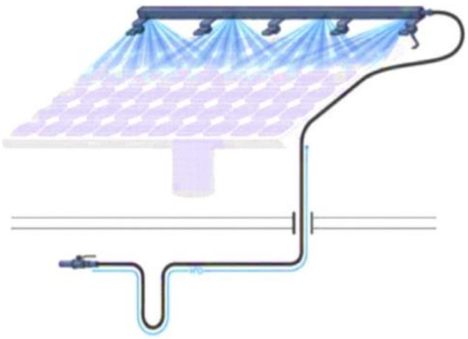


Fig. 6 Illustrates the sprinkling of water.

Fig. 7 Illustrates liquid immersion refrigeration.

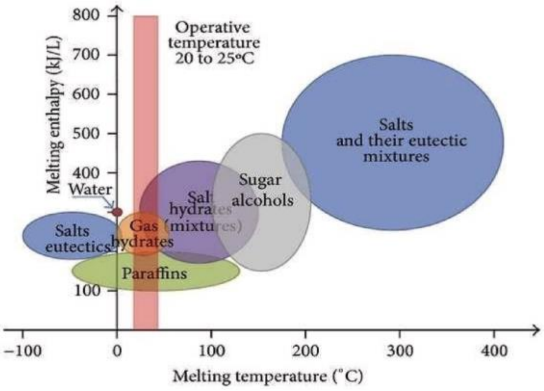


Fig. 8 Shows the melting temperature of common PCM.

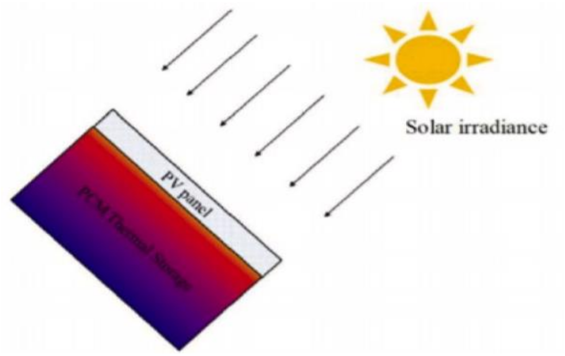
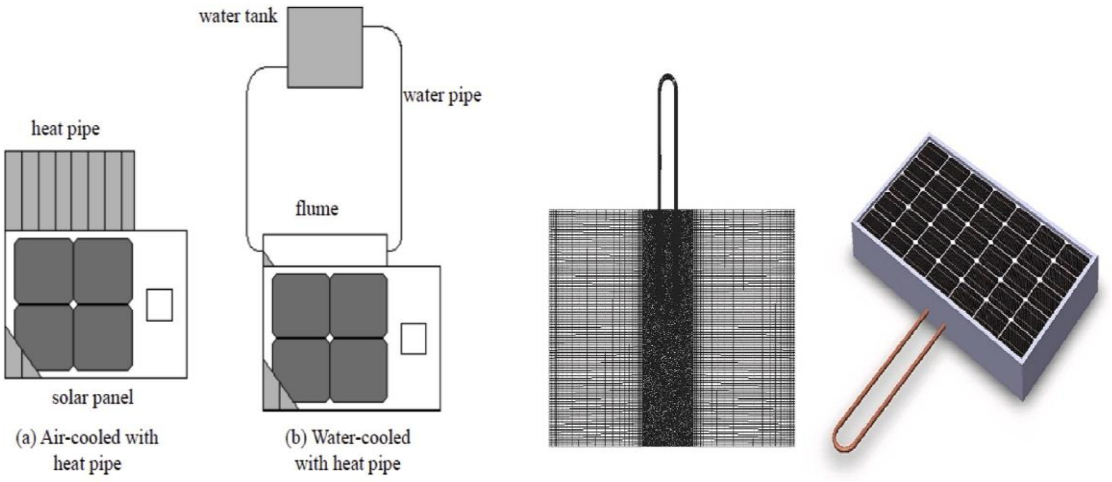


Fig. 9 P-V Schematic linked to PCM

3.7. Heat exchanger, fins, expanded surfaces, and heat sink

To optimize the passive cooling process of photovoltaic panels, supplementary elements such as heat sinks or fins made of metallic materials that are affixed to the rear of the PV system facilitate convective heat transmission from the air to the panels. In general, heat sinks with high thermal conductivity are situated in the rear of the solar cell.

The heat transfer area between the solar cell and the surrounding environment is increased by a heat absorber. It has tremendous potential for chilling photovoltaic panels on account of its low cost and straightforward design. Limited physical testing has been conducted regarding the functionality of heat absorber plates. Furthermore, micro-channels are regarded as a photovoltaic cooling method that facilitates the transmission of heat with a substantial capacity (Figures 12 and13). Parkunam et al. devised a method to increase the electrical efficiency of solar panels by employing a capillary structure comprised of copper and aluminum fins in addition to heat sinks to aid in cooling.



(a) Air-cooled with heat pipe

(b) Water-cooled with heat pipe

Fig.10 Heat conduit schematic with air and water cooling

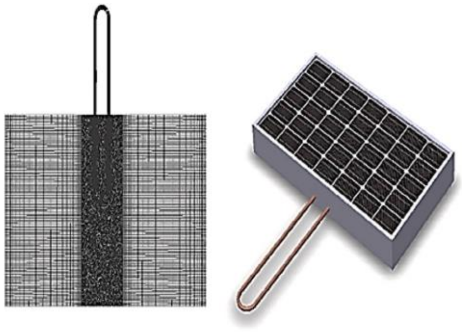


Fig. 11 PV panel model with heat pipe.

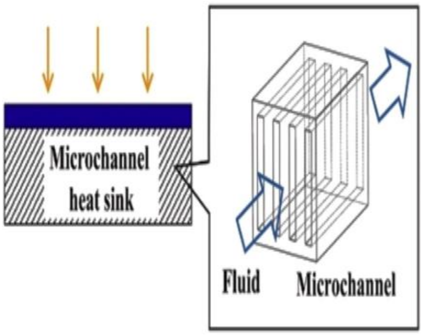


Fig. 12 A schematic representation of a photovoltaic panel in corporating a thermal sink

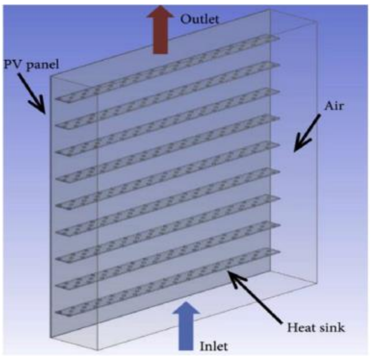


Fig. 13 Micro channel heat sink schematic diagrams.

3.8. Heat exchanger microchannel

The heat exchanger method is among a number of prevalent cooling techniques. The heat exchanger technique facilitates the transfer of heat from one medium to another or from one fluid to another. Attain peak performance at elevated temperatures. Utilizing CFD Analysis, the optimal flow rate of the cooling medium was determined in order to maximize efficiency.

Micro-channel cooling may represent a viable approach to ensuring that photovoltaic cells operate at their utmost efficiency. Micro-channels have the potential to function as a hybrid medium for photovoltaic-thermal systems (PVTs). PV cells may be cooled through the utilization of wind currents and aluminum skirts.

Efficient fabrication of micro channels and enlarging the experimental setup constitute the primary obstacles encountered in the development of micro channels.

3.9. Photonic cooling or radiative sky cooling

A novel framework for photovoltaic (PV) cooling has been established through the interplay between the capacity of outer space to absorb heat and atmospheric visibility in the 8–13-μm wavelength range. In order to apply the radiative theory, the temperature difference between objects in outer space and those on Earth must be utilized. The radiative function facilitates cooling when an object is oriented toward the Sun. Recent research and application has also focused on the utilization of radiative cooling to reduce photovoltaic temperatures (Fig.14).The experimental utilization of solar absorbers for radiative cooling was investigated by Zhu et al. [40]. It was conclusively demonstrated that a transparent photonic structure in the range of sunlight wavelengths functions as a black body in the range of thermal wavelengths. Placing a photonic structure beneath a solar panel enables it to be cooled radiatively while maintaining solar absorption. The results indicated that the cell temperature decreased to 13 degrees Celsius due to radiative cooling. Sky cooling through radiation is an example of a passive cooling mechanism. One way in which the thermoelectric generator-based system takes advantage of the temperature difference between Earth and outer space is by maintaining the frigid side several degrees below normal.

3.10. Cooling via nano fluids

MiXED nano particles with water are employed as nano-fluids for the purpose of cooling photovoltaic panels and improving overall system performance [42]. In order to improve heat transfer, different weight percentages of the various nano particles are utilized. These nano particles are utilized: Boehmite, Aluminium oxide (Al2O3), Zinc oxide (ZnO),Titanium oxide (TiO2),Magnetite (Fe3O4),Silicone carbide (SiC), and copper oxide (CuO)

3.11. Peltier (thermoelectric) refrigeration

Moreover, thermoelectric (T.E.) cooling is an additional method utilized to reduce the temperature of photovoltaic panels. By utilizing the thermoelectric module, surplus heat from the photovoltaic panel is captured and converted to electrical energy. Utilizing electrical energy, the Peltier effect-based system is utilizing the PV panels for cooling purposes. The fundamental concepts underlying thermoelectric cooling are the Peltier effect and the see-back effect. The Peltier effect manifests itself as a thermal gradient in a designated path within an energized junction. It induces a chilling effect on the opposite side of the junction and generates heating on one. Flow rates for cooling and heating are determined by temperature and voltage/current differences. The PV-TEC methodologies have been described to a restricted extent thus far.The diagram of a photovoltaic cell in corporating a TE module is illustrated in Figure15. The P.V. cell cooling process was simulated by Najafi and Woodbury [45] using a Peltier element. It has been demonstrated that thermoelectric cooling can be successfully integrated in to high concentration PVcells.

A laboratory investigation was conducted by Borker et al. on the thermoelectric cooling of a PV module. The findings indicated that the implementation of T.E. cooling increased the performance of the photovoltaic panel from 8.35–11.46% to 12.26–13.27%.

Benghanem et al. noted that the implementation of T.E. modules resulted in a reduction in the temperature of the PV cells from 83^{0}C to 65^{0}C. The T.E. system utilizes electrical energy generated by the panels to provide a cooling effect. In order to ensure dependability, the energy consumption of the T.E. module must be considerably reduced in comparison to the electricity generated for chilling photovoltaic panels.

3.12 Cooling via evaporation

By utilizing water evaporation to cool the panels in the same way that perspiration helps cool the epidermis on a hot day, evaporative cooling is an ideal option. By utilizing water evaporation in conjunction with the ambient air, it attains phase equilibrium. Evaporative cooling is the most viable, practicable, and promising method for regulating the temperature of photovoltaic panels. Despite the apparent potential advantages of evaporative cooling, this cooling method has been implemented in a limited number of studies. The following are crucial elements of evaporative cooling:

- Ease of implementation.
- Much lower cost
- The strategy works well in hot and dry climates (see Fig. 16).

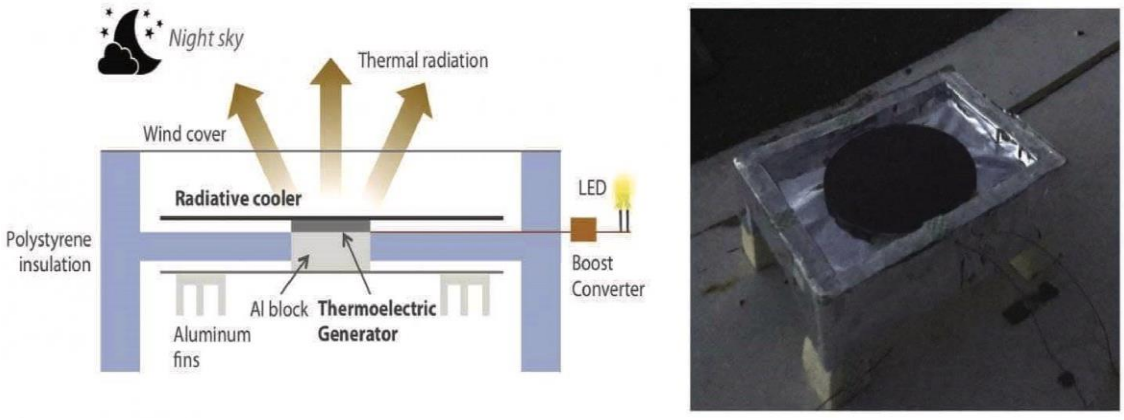


Fig. 14. Passive Radiative sky cooling

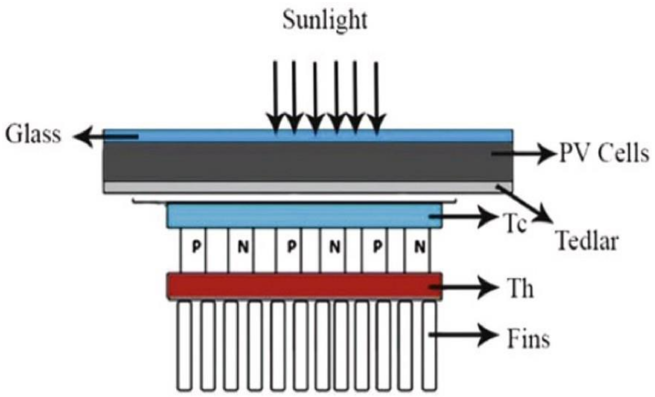


Fig. 15 Schematic of P.V. cell with T.E. module

3.13. Cooling of the spectrum filter (optical beam splitter)

Fluids that exhibit selectivity in absorption or function as optical filters on solar photovoltaic systems include vapor, organic liquids, and nano-fluids [53,54]. The utilization of a liquid as the optical filter between the solar cell and the sunlight constitutes optical beam split strategies (Fig. 17). It is conceivable that liquid filters could be autonomously monitored utilizing pumps, magnetic or electric fields, and temperature fluctuations spanning the entire solar spectrum from ultraviolet to near-infrared. The clear fluids listed below were utilized as optical filters.

- coconut oil,
- silicone oil,
- glycerine,
- ethylene glycol etc.

These liquid spectrum filters are affixed to a thermally shielded photovoltaic module. The filters ensure that the P.V. receives only the spectrum that is usable, filtering out the rest. In a P.V. cell experiment involving multiple optical filters, coconut oil demonstrated superior performance compared to water and silicone oil.

3.14. Multi-concept/hybrid cooling systems

The components of a standard PV/T device are a photovoltaic module and a thermal absorber. Simultaneously increasing the electrical and thermal outcomes is not feasible in the PV/T system. Solar collectors designed for hybrid PV/T systems have the potential to operate at a cumulative capacity of approximately 80%. However, research examining hybrid cooling systems that utilize multiple configurations simultaneously, including heat pipe heat sink; heat sink PCM; PV/T PCM and PCM nano-fluid is uncommon. The investigation and comparison of a PV/T-based

PCM system incorporating nano-fluid and conventional P.V. modules are presented. Karami and Rahimi utilized water-based Boehmite at a concentration of 0.01 wt percent to chill photovoltaic panels, and they observed a 27% increase in efficiency. PV/T integrated systems are distinguished by the following functions in the temperature range of $30–100^0$C. The design of thermal systems must strike a balance between the increased performance temperatures and the decrease in photovoltaic cell efficiency. Technologies that require tremendous amounts of electrical and thermal energy for residential and commercial applications generate substantial financial returns.

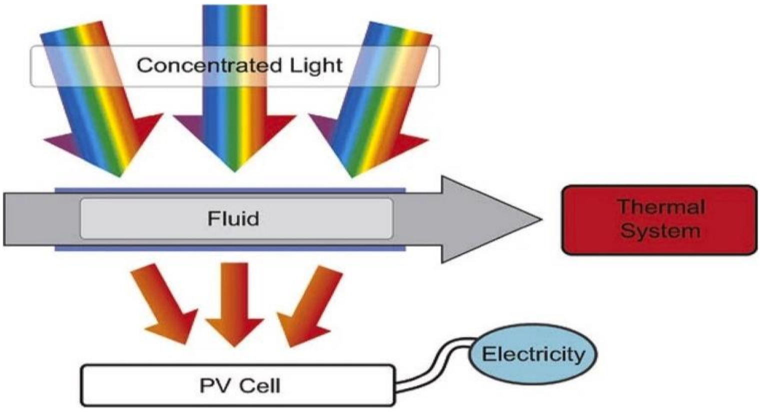


Fig. 16 Scheme of Evaporative P.V. cooling scheme proposed

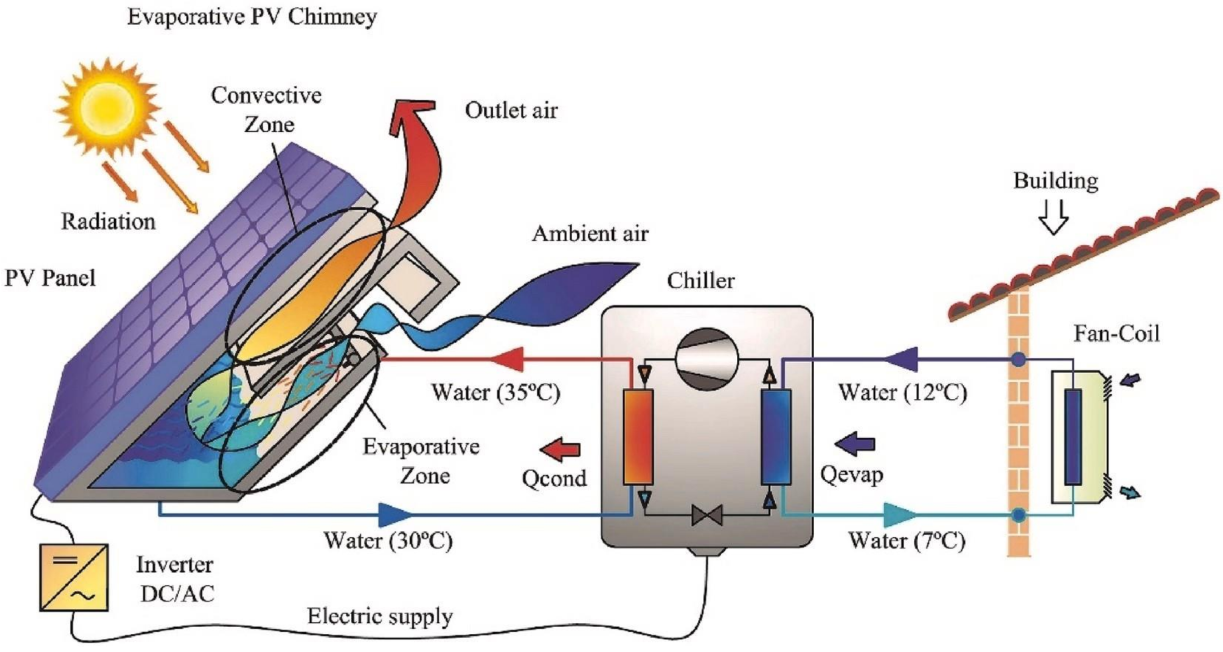


Fig. 17 Illustration of a PV cell with a fluid serving as an optical filter

IV. CHALLENGES AND FUTURE PROSPECTS

Due to the significant impact of heat on the electrical efficiency of P·V, extensive efforts were made to discover cost-effective methods of cooling P.V. modules. The following is a compilation of the difficulties encountered in the development of an economically efficient photovoltaic cooling system. It is important to acknowledge and comprehend the several factors that influence cell temperature and how potential cooling systems might be impacted. Designing a system requires careful consideration of various elements, including module orientation, placement, and cooling system components. The cooling process must take into account the high surface area and the significantly low power output per module. In order to provide a uniform distribution of temperature across the working surface, the degradation of the modules rises as the hotspot grows.

Weighing the increased initial expense against improved performance. Thus, for a cooling system to be considered effective, it must be highly affordable and not substantially increase the overall cost of the system.

Failure to account for environmental factors during system design may result in maintenance expenses that surpass the advantages of enhanced power generation. There are multiple metrics and variables used to assess the efficiency of P.V. cooling systems, despite the absence of standardized testing protocols. In order to achieve optimal cooling performance, it is essential to tackle these difficulties throughout the design phase of a photovoltaic cooling system. In summary, successfully cooling photovoltaic (P.V.) modules poses several hard obstacles, which have prompted continuous study in this area and offer potential for further enhancements. Air and water-based technologies in cooling systems are well-developed and extensively documented. Nevertheless, refrigerant-based systems and heat pipes are still being developed, but their widespread adoption is hindered by several technical and cost-related challenges. Heat sinks offer great promise as cooling devices for P.V. panels and should be further developed. However, there is a scarcity of study on the subject of evaporative cooling for P.V. panels.

The future of TEG in this regard remains promising, but much progress is needed to make it commercially viable. An ideal system should prioritize efficiency while also considering the costs associated with the TEG 0s. The advancement of photonic methods for cooling solar cells presents significant prospects, as demonstrated by the aforementioned description. Nevertheless, the current solutions only utilize a fraction of the potential benefits that photonic engineering might offer for cooling solar cells. Passive air cooling with fins may be the feasible choice when considering both technical and economic factors. If the cost of PCM based cooling decreases significantly, it could become commercially viable. The use of passive cooling and other active cooling methods was not economically feasible for the phase change material (PCM). A water-based active cooling system has the potential to be a cost-effective solution through the optimization of the system and intelligent control of the process. Alternatively, a combination of at least two of these strategies can be employed simultaneously to effectively reduce the temperature, resulting in a more remarkable outcome than using any single way alone.

V. CONCLUSION

The objective of this study was to evaluate and compare the most favorable photovoltaic (PV) cooling methods in order to obtain a comprehensive understanding of their design, application, and potential for future development in PV systems. Here are the important conclusions derived from the analysis of several photovoltaic cooling systems. The results indicated that active water cooling is the most straightforward and efficient cooling method and should be further researched. Nevertheless, the implementation of active water cooling is frequently impractical. In order to achieve effective water cooling, it is necessary to have a consistent source of cool water in the environment, and the system being cooled must be of significant size to compensate for the energy usage.

The utilization of natural convection for passive cooling of the P.V. system has been identified as the most straightforward approach. However, it is important to note that this technology has certain limitations. In addition, air is a less efficient coolant compared to water.Water-based cooling systems are most suitable for applications where there is a match between hot water and energy requirements, such as in restaurants, hotels, and process industries. Another benefit of this technique is the removal of dust accumulation on the P.V. module. Furthermore, it has the potential to be utilized in the agricultural sector, since the water employed for cleansing can be reclaimed for the purpose of irrigating agricultural crops.

PCM cooling is the most effective way due to its superior energy density per unit volume. It can be deduced that both air and water cooling methods have been widely utilized since they may supply more thermal energy for various applications. While there are numerous alternative techniques, it is necessary to evaluate the performance efficacy of different cooling systems to determine their feasibility. The objective is to improve, streamline, and expand each technique to enable the efficient deployment of large-scale solar farms as required.

Identifying a straightforward and affordable system from the presented options is challenging due to a lack of economic effectiveness data. Subsequent investigations should prioritize the examination of economic analysis and its evaluation of the environment. The future trajectory of technological advancement should prioritize the development of hybrid cooling techniques, with the primary goal of consistently and effectively maintaining low and stable surface temperatures. Subsequent investigations should prioritize the examination of either active water cooling or combined heat pipe and sink cooling, both of which show potential for effective cooling.

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