Cooling Practices towards Enhanced Photovoltaic Systems Performance

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Abstract: *The overuse of resources by humans is a major cause of our present worldwide energy environment, as evidenced by Earth Overshoot Day, which falls on July 29, 2021, and represents this trend. Utilization of energy exceeded Earth's yearly regeneration capacity as of July 30, with a 1.73× overshoot predicted by year's end. Considering installed pv capacity predicted to increase significantly—potentially achieving 4,674 GW by 2050 and contributing 16% to global electricity production—solar energy looms as a key answer. With only 1.5 hours of annual sunshine exposure, solar power, a clean, renewable power source, has enormous potential to supply the world's energy needs. Essential to this shift are solar energy sources, which have a wide range of uses from home to business because of their affordability, durability, and direct conversion performance Optimizing solar panel performance requires reliable cooling systems, which have an effect on both operational effectiveness and financial sustainability. The energy consumption and effectiveness of cooling techniques fall into two categories: active and passive. Using phase change materials (PCMs) or natural convection, passive cooling offers potential efficiency benefits with the need for additional power consumption, making it appropriate for a variety of climates and budgetary constraints. Research has shown that passive cooling, with techniques like external shading and PCM-enhanced walls, can reduce the usage of energy by upwards of as 70%. In tropical settings, plant cooling and coir pith are examples of passive cooling strategies that have been shown through study results to improve module performance by controlling temperature swings.*

Keywords: *Solar energy, photovoltaic systems, passive cooling, phase change materials, energy efficiency*

I.INTRODUCTION

The current global energy context is characterized by the energy consumption of humanity, which has reached impressive values in recent years. Thus, in the current year (2021) the well-known Overshoot Day was “celebrated” on 29 July. This meant that humanity had already used up all of the restorable resources of 2021 [1]. From 30 July we started consuming more resources than the planet could regenerate in a year [2]. Therefore, by the end of the year 2021, the energy consumption is projected to reach about 1.73× Earth’s resource regeneration capacity. It is a global emergency and every small step in reducing this tendency to over consume energy will become decisive in this fight.In December 2019, global accumulative capacity of the installed photovoltaic modules had reached 653 GW with the expectation to reach 1,583 GW by 2030 and up to 4,674 GW by 2050 at a share of 16% of the total energy production around the world as indicated in Fig. 1. [3]. As the largest producers of solar energy, China and India produce almost half of the current global solar power energy [4]. Solar energy is a clean and sustainable source of energy [5]. It is involved directly or indirectly in the vast majority of other renewable energy sources, and it is also related to the conventional fuels—as most of them are the result of photosynthesis. The solar energy incident on the Earth could cover the annual energy demand for the entire world in only 1.5 h [6]. Photovoltaic systems find wide-ranging applications, extending beyond residential and commercial use to serve as power plants. Their popularity stems from their cost-effectiveness and the direct conversion of sunlight into electricity. Additional advantages include their quiet, low-maintenance operation and extended lifespan, as they have no moving parts [7].

A successful cooling system must significantly increase the module’s efficiency in a much lower payback period. The cooling systems are mostly classified into active and passive. Active cooling systems consume additional power during the heat dissipation process by facilitating cooling via specialized flow ducts or spraying water on panel surfaces [8]. Whereas passive cooling techniques draw out heat without any additional power consumption, through natural conduction or convection. The medium in both the systems can be air, water (natural coolant), or artificial refrigerants [9].

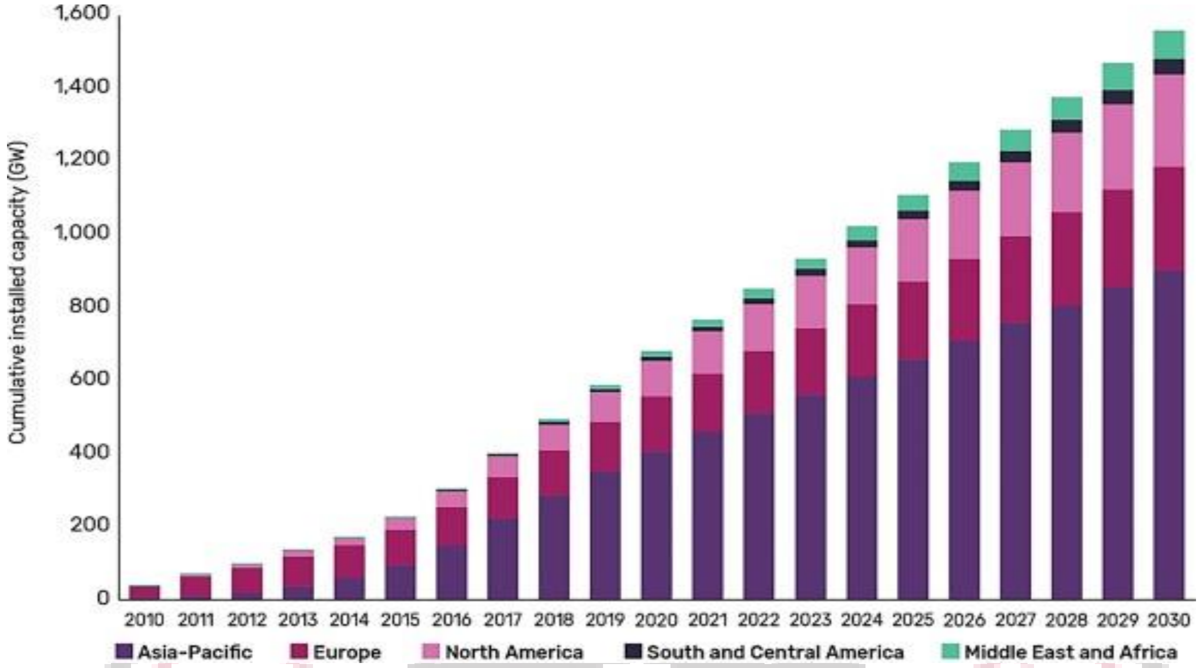

Fig. 1. The cumulative capacity of installed PV modules by regions within 2010-2030 [4]

The cooling techniques portrayed in this figure are categorized into four major types: Active Cooling, Passive Cooling, PCM Cooling, and PCM with Additives. Active Cooling, here included, are techniques such as forced air cooling, forced water cooling, and PV/T systems, among others, which require an input of external energy for the purpose of heat removal.

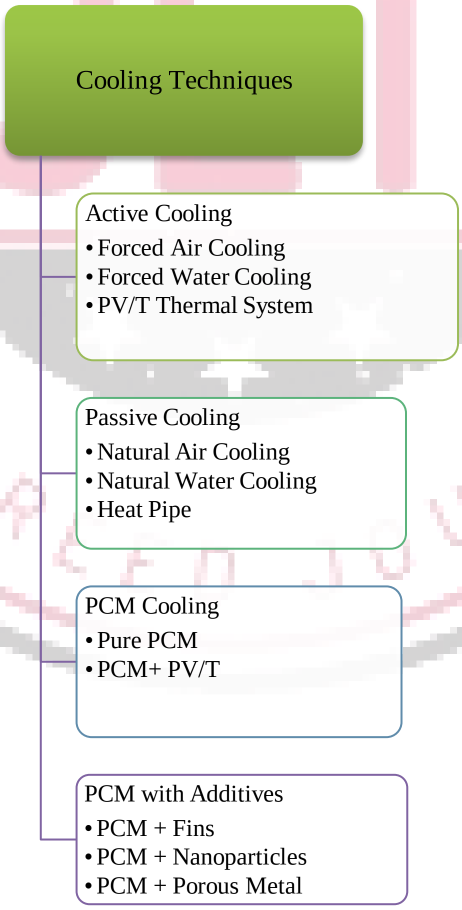

Fig.2. Different cooling techniques [10]

In terms of Passive Cooling, these include no input of external energy, with examples such as natural air cooling, natural water cooling, and heat pipes. PCM (Phase Change Material) Cooling refers to cooling that uses materials to absorb or release heat during phase change; these are further divided into Pure PCM and PCM with PV/T systems. Last are PCM with Additives, in which the features by which PCM cools are enhanced by further things or structures such as Fins, Nanoparticles, or Porous Metal so as to enhance thermal conductivity and heat transfer.

II. LITERATURE REVIEW

Application of the passive approach as a non-mechanical method is an effective technique to tackle high energy consumption as well as diminishing the destructive effects of buildings on the environment. Using passive cooling can lead to peak load reduction as well as peak load offset, diminishing the interior temperature fluctuation, maintaining indoor air temperature in a comfortable range which consequently reduces fossil fuel usage as well as decrease the greenhouse gas emission.

Song, Y. L. et al. (2021) [11], using passive approach from the economic point of view was discussed. The competition between cost saving (owing to applying passive methods) and added cost (owing to the initial investment, maintenance and operation cost) can specify the usefulness and effectiveness of using passive techniques. In this regard, special points such as building function, ventilation requirements, sensible and latent heat gains, the ability of any technique to save energy, geographical location, user financial ability, initial investment, maintenance and operation cost, regional climate data should be taken into account. Literature review affirmed that owing to applying passive approaches in building, energy consumption is diminished by 8%–70% (using external shading), 37% (utilizing cool colored paints roof), 25% (Creating green space), 7.88% (construction of the prismatic building), 32%–100% (using vegetation-based wall), 50% (using PCM-base wall), 33% (incorporation of insulation into the wall), 10%–20% (building equipped with solar chimney), 25% (using radiative cooling system). From the economic viewpoint, it was found that through finding optimal passive approaches, life-cycle cost saving reached 52%.

Today, phase change materials (PCMs) have been used as effective potential energy storage elements in buildings due to their excellent thermal energy storage capability and have attracted great attention in ameliorating serious environmental problems caused by greenhouse-gas emissions. Furthermore, PCMs also present some negative impacts, such as leakage during the solid-liquid phase transition, low thermal conductivity, high supercooling, weakening mechanical properties, and “season adaptable problems”. There is moreover difficulty in the measure the thermophysical properties of composite PCM contained building components, limit their future development.

Li, C. et al. (2023) [12], they summarize the main characteristics of PCMs for building envelopes. The design and shape stabilization methods of composite PCMs are comprehensively discussed. A special attention is given to overview the methods to address “season adaptable problems” during the real applications of the PCMs in building and, the test and heat transfer mechanisms are discussed. It was found that using biomass-derived carbon as supporting material is a low cost, environmentally friendly way to fabricate outstanding performance composite PCMs; adopted multi-PCMs is an important way to solve “season adaptable problem”. Finally, the crucial conclusions and future recommendations are also provided to guide scholars on research for further improvements.

Ramkiran, B. et al. (2021) [13],presents the experimental studies of different passive cooling techniques to analyze the electrical power improvement and temperature reduction of a 50 W polycrystalline PV module. Plant cooling, greenhouse cooling, greenhouse + plant cooling, coir pith, and phase change material cooling are the various approaches are used in the analysis. The percentage of electrical power improvement and temperature of various passive cooling techniques are compared with solar modules without cooling. The maximum percentage power improvement (11.34%) was found to be in coir pith cooling with an average maximum power of 36.38 W. The maximum temperature reduction was observed to be 14 °C in case of plant cooling with a greenhouse. Considering the electrical power improvement and temperature reduction, coir cooling and plant cooling were found to be best suited for the given climatic conditions amongst all cooling techniques. The results also showed that the reduction in temperature does not always give rise to the increase in power as it was depicted in the case of greenhouse net cooling and plant cooling with greenhouse. This kind of cooling technique is best suited for agro-based countries in tropical regions.

The performance of lithium-ion battery is greatly affected by temperature, so the battery module must be equipped with an effective thermal management system (TMS) during operation.

Ren, R. et al. (2021) [14], studied about a new type of active air cooling TMS based on U-shaped micro heat pipe array (MHPA) is developed to reduce a battery's temperature rise and improve the temperature uniformity of the battery module throughout the entire charge and discharge process. Modules with and without U-shaped MHPA are established for comparative experiments. They can dissipate heat in three methods, namely active air cooling with U-shaped MHPA (AAC-MHPA), passive air cooling with U-shaped MHPA (PAC-MHPA), and passive air cooling with no U-shaped MHPA (PAC-NMHPA). Results show that under 2C constant current charge and 3C constant current discharge conditions, the maximum instantaneous highest temperatures of AAC-MHPA and PAC-NMHPA are 51.70 °C and 57.83 °C, respectively. This outcome demonstrates that the thermal management performance of AAC-MHPA is the best. This cooling method has good thermal management performance even under high charge and discharge rates conditions.

Photovoltaic systems convert only a small amount of incident solar insolation into electrical energy while the rest is dissipated into heat. The increase in the PV cell temperature decreases significantly the electrical efficiency by about 0.5%

for each 1 °C rise. Hence, it is necessary to keep the module temperature at low values to improve the efficiency and to minimize the thermal degradation effect.

Dida, M. et al. (2021) [15], in this research paper, a passive cooling system was developed to mitigate the overheating of PV modules in order to enhance their performance. The developed cooling system is based on water evaporation and the capillary action of the burlap cloth that was attached directly to the rear surface of the module. Thermal and electrical characteristics of the modules (with and without cooling) were investigated experimentally under outdoor conditions during summer days of a hot climate region. Experimental results showed that a PV module temperature reduction of 20 °C (26%) was achieved with the help of the developed evaporative cooling system leading to an important increase of 14.75% in the electrical efficiency. The results also revealed the high effectiveness of the developed cooling system in the reduction and the maintaining of a uniform temperature distribution over the PV module throughout the day. Furthermore, this cooling system has many advantages such as being environment-friendly, low investment cost and low water consumption 0.39 L/h.

In this era of a sustainable energy revolution, energy storage in batteries has come up as one of the most emerging fields. Today, the battery usage is outracing in e-vehicles. With the increase in the usage of batteries, efficient energy storage, and retrieval in the batteries has come to the foreground. Further, along with a few other parameters, the operating temperature of the battery of an electric vehicle plays a vital role in its performance. Also, the internal heat generation limits the performance of the lithium-ion batteries. The operating temperature range of an electric vehicle lithium-ion battery ranges from 15°C to 35°C and this is being achieved by a battery thermal management system (BTMS). Owing to the efficiency of these systems, a considerable amount of work has been performed beforehand.

Tete, P. R. et al. (2021) [16], take this research forward, this paper gives a comprehensive review of all the experimental and numerical analyses conducted on various BTMS techniques for electric and hybrid vehicles where the battery cooling systems with air, liquid, phase change material, heat pipe, refrigeration cooling methods are discussed. The significant findings and outcomes of the experimental, simulation, and modeling work on BTMS in recent past years are reviewed in depth. Besides that, a systematic review of hybrid battery cooling systems is also presented in this paper. Lastly, a summary is made of all the developed BTMS along with their experimental, mathematical, and computational simulation models.

III. FUNDAMENTALS OF PV COOLING

Numerous environmental factors like wind direction, solar irradiation, dust accrual, and humidity influence the change in PV panel surface temperature. The PV panel is open up to the environment to harness more power and all of these factors are uncontrolled.There are two types of PV panel cooling techniques i.e., active and passive. Active cooling of a photovoltaic panel usually requires the use of devices like a pump to circulate water or forced air to eliminate the heat. The passive cooling technique mainly installs fins at the rear of PV panels to improve natural convection and radiation heat transfer [17].

A. Air-Based Cooling Technique

PV panels can also be cooled through a forced and natural air. It is further divided into active and passive cooling. Passive cooling method uses a natural airflow over a hot surface while active cooling. Active cooling is performed with forced airflow with embedded channels in various heat sinks and fins at the back of a panel. Such kind of cooling is generally used for its least operational, and maintenance cost. The major disadvantage of this kind of cooling is an enormous heat sink area for improving the operating temperature of a panel to standard testing conditions.

B. Water-Based Cooling Technique

This is more efficient in heat dissipation than air-based. This is accomplished with water-based collectors of tubes and fins to increase the heat transfer in this more operational and maintenance costs, the flow rate of water, keeps the optimal operating temperature of a panel, which is improved by a combined flow of water.

C. Water Flow over Panel Water Spraying, Jet Impingement Cooling Technique

Highest efficiencies of panels with cleaning of their surface, prevention of soil deposition. This wastes most water in hot seasons because of evaporation at a high operational temperature. General extra power is required for water-pumping, which increases the system cost and lowers the payback time due to power consumption by pump.

D. PCM Cooling Technique

It is a technique that is used by placing the phase change material (PCM) at the back of Photovoltaic. The material extracts and stores heat from the photovoltaic without increasing its temperature. It results in uniform cooling. Created with PVT, the fins, or heat sinks, it results in high efficiency. Incapable of enhancing the efficiency of the PV panels due to its decreased operating temperature. Materials for PCM may degrade after some time due to which their heat absorption also decreases.

E. Hybrid Nanofluid PVT Cooling Scheme

Nanofluids have a considerably higher thermal conductance than basic fluids and are therefore a very active topic in the solar photovoltaic industry. As the volume fraction of nanoparticles is enhanced, heat transfer also increases, giving rise to increased thermal conductance of nanofluids. For this reason, nanofluids are employed to improve heat evacuation, which in turn boosts the electrical efficiency of the PV panels.

In comparison with water-based systems, air-based cooling systems generally have lower thermal performance. However, this can be improved by using single and double-pass setups, wherein the convective heat transmission area is increased through the use of fins, thin-metal sheets, or other porous mediums. In fact, some studies have shown that such designs can enhance radiative and convective heat transmission and could, therefore, act as heat sinks. Radiative and convective heat transmission could be easily carried out in designs where the air travels above the surface in comparison with any setup design wherein the air travels below the absorber's surface. Radiative heat transmission is improved when designs are used that travel below the absorber's surface. In fact, water-based cooling techniques have been proved to be more effective simply because of water's better heat transfer. Convection methods like free and forced as well as front water cooling and also heat pipes and immersion have demonstrated great efficiency improvements and temperature drops. The experimental study showed electrical gains due to reduction in temperature with water flow in the front of PV modules by curbing reflection and reducing temperature greatly. Conversely, various water-cooling methods have also shown efficacy in reducing temperatures. Moderately improved temperatures have been demonstrated with different spray regimes.

F. Phase Change Materials (PCM)

Phase change materials are those that store and release energy while changing phases; that is, while in conditions of changing from solid to liquid or from liquid to gas. In PV cooling, therefore, phase change materials stabilize temperatures and maintain temperature uniformity. Some temperature drops and efficiency improvements with PCM cooling were reported in several studies. Methodical and system-related characteristics of the PCM influence the efficiency and temperature uniformity of the PV systems. Furthermore, PCM contributes to storing and producing a significant fraction of heat, and adding fins enhances convective heat, still improving temperature and controlling efficiency.

G. Pure PCM

Studies have been conducted on the sole impact of PCM to reduce the temperatures of PV panels for efficiency enhancement. The use of finned PCM enhances periodic convective heat transfer significantly, leading to marked temperature reduction and efficiency improvement. Studies have shown that internally finned PCM used in PV panels can reduce temperatures significantly, thereby saving energy particularly in hot climates. Besides, outdoor experiments on PV systems cooled with SiC-water nanofluids have been shown to have better performances compared to water-cooled and stand-alone PV systems. These PVT hybrid systems with nanofluids achieve a reduction in panel temperatures of 16°C, while their electric efficiency and power output are raised by up to 24.12% and 57%, respectively, thus indicating increased potential to enhance PV system performance greatly.

IV. CHALLENGES AND FUTURE SCOPE

A. Technical Issues: Mounting fins on the PV system poses technical challenges. These relate to optimizing fin design for ideal heat transfer without significantly increasing weight or shadowing, which would decrease solar absorption. It also alludes to compatibility of materials and durability under environmental conditions, such as temperature fluctuations and being exposed to the elements [18].

B. Limitations of Current Studies and Knowledge Gaps: Often, current studies do not have sufficient long-term data to allow generalization regarding the durability and maintenance requirements of fins in PV systems throughout the operating life of a system. Many of the studies have been carried out under controlled conditions, which do not mimic the exact situation in which the fins will work, creating gaps in field application knowledge.

C. Practical Considerations in a Real World Environment: Sensible considerations for implementation in the real world would extend to the cost effectiveness of fin installation, the complication of installation, and whether a larger energy gain would result in increased maintenance costs. Installation would need to weigh off an increase in cooling efficiency to additional costs or reductions in performance brought about by actual modifications [19].

V.CONCLUSION

To integrate PV/T systems with heat pumps, it offers great potential for increased efficiency in energy and sustainability. Despite significant progress in the sector of standardized performance measurements, large gaps still exist in system designs and actual application data. Therefore, further experimental and modeling studies are vital, and mainly regarding adaptability to diverse climatic conditions and economic feasibility at scale. In summary, the integration of PV/T with heat pumps provides a promising way for sustainable future energy with enhanced overall efficiency and a lower dependence on fossil fuels; it advances sustainable energy futures.

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