

Performance Degradation and Thermal Regulation in Photovoltaic Modules: A Critical Review of Cooling Approaches

Zulqarnain Hyder¹ , Shahzaib Ali² , Ghulam Mujataba³ , Zaheer Uddin⁴ , Zaryab Basharat^{5*}  and Muhammad Shoaib⁶ 

^{1,6}State Key Laboratory of Multiphase Flow in Power Engineering

^{5*}MOE Key Laboratory of Thermo-Fluid Science and Engineering, Xi'an Jiaotong University, Xi'an, China

²Civil Engineering Department, ³Energy System Engineering Department

Quaid-e-Awam University of Engineering, Science and Technology, Pakistan

⁴Mechanical Engineering Department, Mehran University of Engineering and Technology, Pakistan

E-mail: nainy2k3@gmail.com, zaheer20k2@gmail.com, shahzaib.quest@gmail.com, ghullammujtaba82@gmail.com, shoaibmahar24@gmail.com

*Corresponding Author: 2020me521@student.uet.edu.pk, enr.zaryab@stu.xjtu.edu.cn

(Received 2 August 2025; Revised 5 September 2025; Accepted 5 October 2025; Available online 25 October 2025)

Abstract - The growing global need for sustainable energy has accelerated the adoption of solar photovoltaic (PV) systems as a clean source of power to replace fossil fuels. Nonetheless, environmental and operational conditions, including high temperature, variability in solar irradiance, wind speed, and dust accumulation, have a tremendous effect on PV module performance. Among these, temperature increase is one of the primary issues, as much of the absorbed solar energy is converted into heat, decreasing electrical power efficiency and accelerating module degradation. This review paper thoroughly analyzes the most important parameters governing PV performance and assesses current developments in thermal management approaches aimed at counteracting performance losses. These cooling techniques, including passive and active methods such as natural ventilation, forced air cooling, liquid-based cooling, thermoelectric cooling, and phase change material (PCM)-based cooling, are examined and compared with regard to performance improvement and practical applicability. The paper summarizes existing technological trends, the benefits and drawbacks of different cooling technologies, and future research perspectives aimed at improving the performance, reliability, and longevity of PV systems under different climatic conditions.

Keywords: Photovoltaic Performance, Thermal Management, Cooling Techniques, Phase Change Materials

I. INTRODUCTION

The present global energy needs are largely satisfied through non-renewable resources such as fossil fuels, which are rapidly being exhausted and are a major cause of greenhouse gas emissions [1–3]. The ever-increasing energy requirements in industries and households have made renewable energy sources a focus of interest as an alternative to fossil fuels. The traditional utilization of fossil fuels has raised serious environmental concerns because of the release of greenhouse gases into the atmosphere, which cause global warming and climate change. Energy concerns have been addressed through various technologies to reduce dependence on fossil fuels [4].

Researchers have indicated that the frequency and severity of extreme precipitation events are likely to increase with rising temperatures and higher greenhouse gas concentrations in the atmosphere [5]. Energy research, with its wide range of applications in daily life, is gaining prominence among academics worldwide, driving innovations across various sectors [6–9]. The current global trend in energy research is strongly focused on minimizing energy consumption and carbon dioxide emissions, reflecting a strong commitment to environmentally friendly and sustainable energy sources [10–12]. Renewable energy sources are naturally replenished and provide long-term sustainability. They help mitigate climate change and reduce greenhouse gas emissions. Their efficiency and reliability can be enhanced through continuous research and the integration of multiple renewable energy sources [13].

Solar energy is one of the key renewable energy sources that can be transformed into thermal or electrical power [24]. To satisfy increasing energy demands, scientists are advancing technologies, particularly photovoltaic (PV) panels, to maximize the efficient conversion of sunlight into electricity [25, 26].

This pollutant-free renewable energy technology helps reduce global warming, while offering advantages such as low operating costs, minimal maintenance, and high power density, highlighting the benefits of solar photovoltaic (PV) energy [26–28]. All renewable energy ultimately originates from solar radiation. It can be converted directly or indirectly into electrical energy through photovoltaic (PV) systems and thermoelectric collectors, respectively [29, 30].

Specifically, photovoltaic (PV) and wind energy have been regarded as the most suitable and economically viable technologies for large-scale adoption and power generation, leading to their consistent and significant expansion in the global energy mix [31].

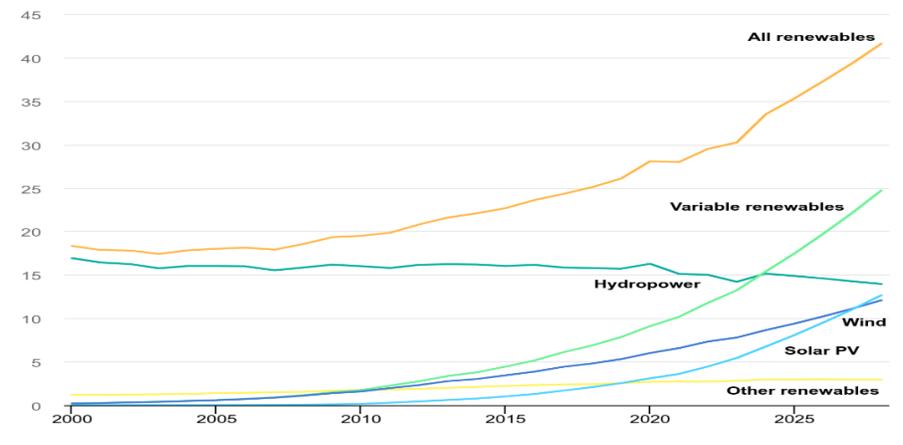


Fig.1 IEA Paris, Shows Usage of Renewable Energy from 2000-2025

TABLE I ILLUSTRATES RENEWABLE ENERGY SOURCES

Sources	Definition	References
Wind Energy	The kinetic energy of wind creates electricity when wind turbines are rotating.	[14]
Solar Photovoltaic	Power production using solar panels with the help of sunlight.	[15]
Solar Thermal	Produces steam by heating fluids that can be utilized to heat or drive a generator.	[16]
Biomass Energy	Organic resources (wood, waste, etc.) are used to generate heat or power.	[17]
Biofuels	The organic matter is turned into liquid fuels and used to produce electricity.	[18]
Hydrogen Fuel cell	Water and energy are produced as a result of the chemical conversion of hydrogen and oxygen. (However, Hydrogen must be green).	[19]
Tidal Energy	uses the energy which the rising and falling tides produces power.	[20]
Geothermal Energy	Use of heat in the middle of the earth by using underground hot water or steam to heat and produce electricity.	[21]
Wave Energy	The movement of waves in the ocean is utilized to produce electricity.	[22]
Concentrated Solar	The sunlight is concentrated on smaller surfaces by mirrors and lenses and used to produce electricity with the help of the traditional steam or gas turbines.	[23]

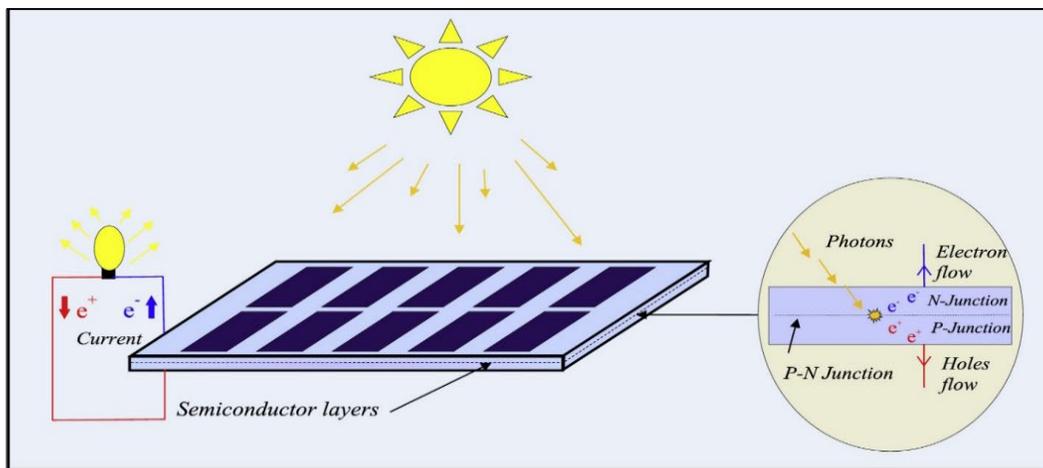


Fig.2 Basic Working of PV Panels [32]

A technology known as photovoltaic (PV), which converts solar irradiance with photon energies above the semiconductor band gap directly into electricity, has achieved enormous advances in research and commercial applications; however, further improvements are still required in terms of efficiency and cost reduction [33]. Photovoltaic (PV) technologies include monocrystalline and

polycrystalline silicon (first generation) as well as thin-film cells (second generation), such as amorphous silicon (a-Si), CIGS, and CdTe. The global market is dominated by first-generation silicon panels (~95%) because they offer higher efficiencies, with monocrystalline panels achieving approximately 21.7% and polycrystalline panels approximately 17.8% [34, 35].

II. PROBLEMS IN SOLAR PHOTOVOLTAIC PANELS

The intensity of solar radiation, the materials used in solar cells, and their operating temperature are the three factors that determine the efficiency of converting sunlight into electricity in PV panels [36, 37]. Typically, the lifespan of photovoltaic modules exceeds 20 years; however, during their lifetime, various factors affect their operation [38–40], including hail, dust, and surface operating temperature, which may reduce conversion system efficiency [41, 42].

Photovoltaic cells convert only a small proportion of solar energy into electrical power, with the majority (approximately 85–90%) being absorbed as heat. This heat absorption raises the operating temperature of the PV module, thereby decreasing its electrical efficiency. Such thermal stress can also accelerate the aging process of the cell over time and may cause structural damage [4, 43].

The electrical power output of solar panels decreases significantly as the solar cell temperature rises. Typically, a

solar cell converts only 5–20% of the incident solar radiation into electrical energy, while the absorbed heat can increase the cell temperature to around 70°C [44]. Although solar PV is a viable substitute for fossil fuels, it still faces the challenge of relatively low efficiency. The theoretical efficiency of commercial PV cells is about 29%, whereas current practical efficiencies reach up to approximately 26% [45]. Various factors are responsible for the degradation of PV panel efficiency explained in figure below [47]

TABLE II HEAT LOSS FROM PV PANEL [46]

Heat loss from module	%
Conduction by rising	2%
Convection via the top of the roof	42%
Convection coming from the bottom side	24%
Radiation originating from above the surface	21%
Radiation originating from the below surface	11%

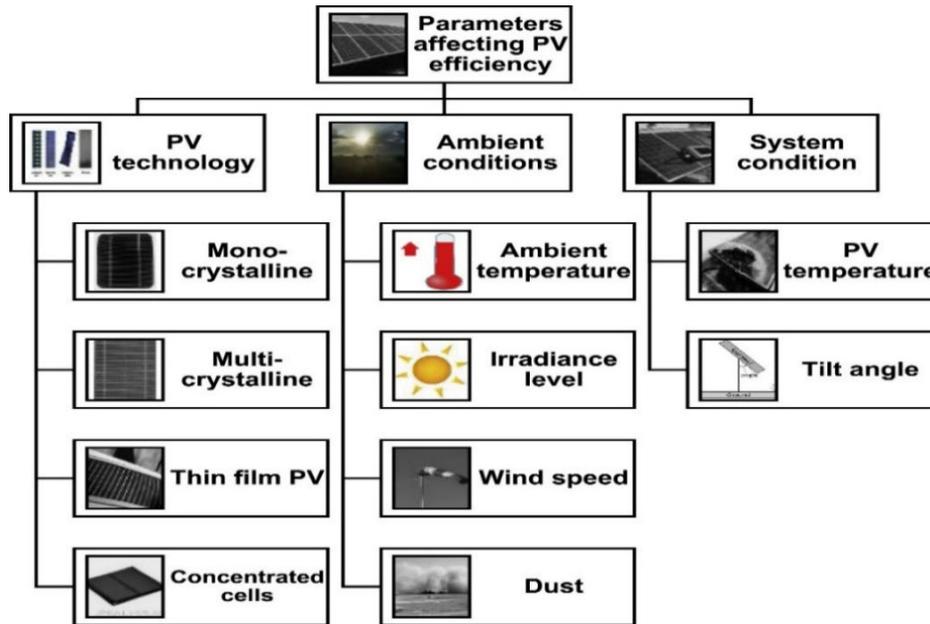


Fig.3 Various Parameters Affecting PV

A. Ambient Temperature

Research has revealed that the effectiveness of crystalline silicon cells is negatively influenced as temperature increases. PV systems perform best at room temperatures of 25°C or lower, with efficiencies ranging from 15 to 20% [48]. The open-circuit voltage (VOC) drops significantly as the solar panel temperature rises above 25°C, whereas the short-circuit current (ISC) increases only slightly.

This temperature dependence is measured using the temperature coefficient, which indicates the change in output for each degree Celsius under standard conditions. For example, a temperature coefficient of 0.5% implies that the maximum power output decreases by 0.5% for every 1°C increase in temperature [46].

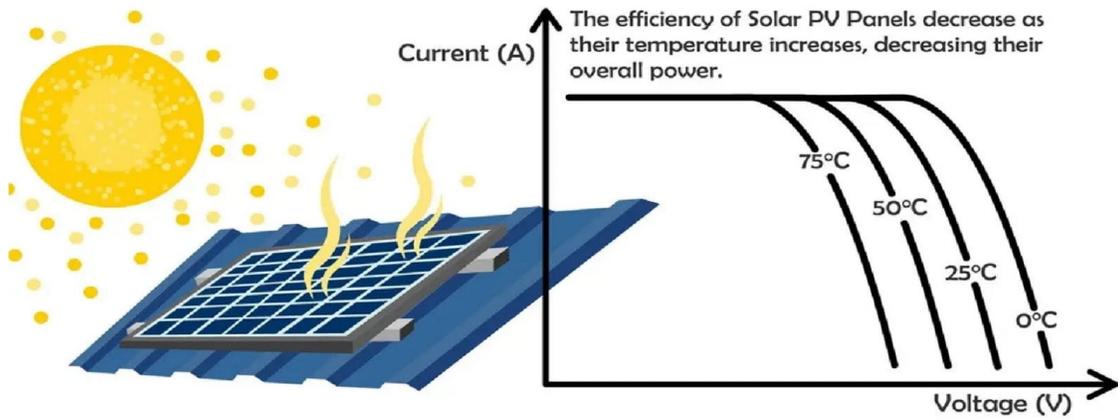


Fig.4 Effect of Temperature on PV [49]

The relationship between module temperature and power loss for three PV technologies (Si-mono, Si-poly, and CIGS) at temperatures ranging from 25°C to 55°C is illustrated in

Figure 5. The power loss varies with ambient temperature, and the values are similar across all three technologies.

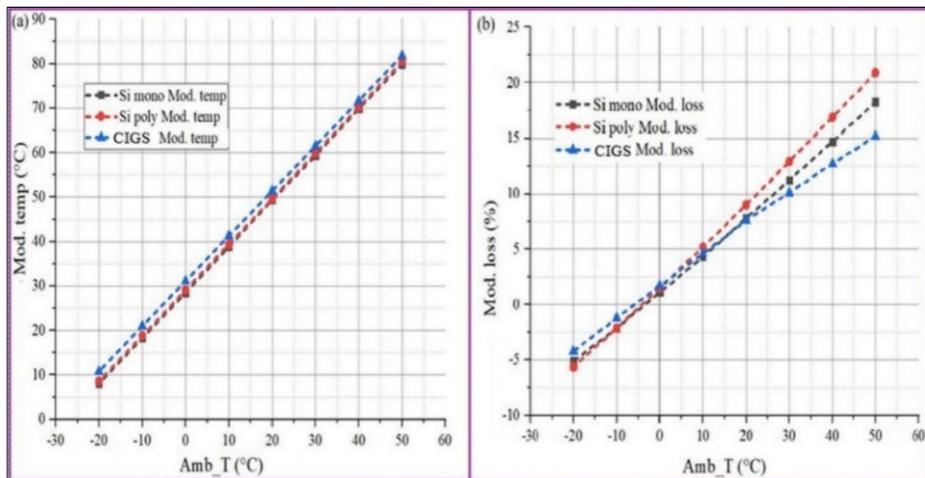


Fig.5 Influence of Ambient Temperature on the Performance of a PV System, with Respect to (A) The Temperature of the Modules and (B) The Loss of Modules. [50]

B. Irradiance Level

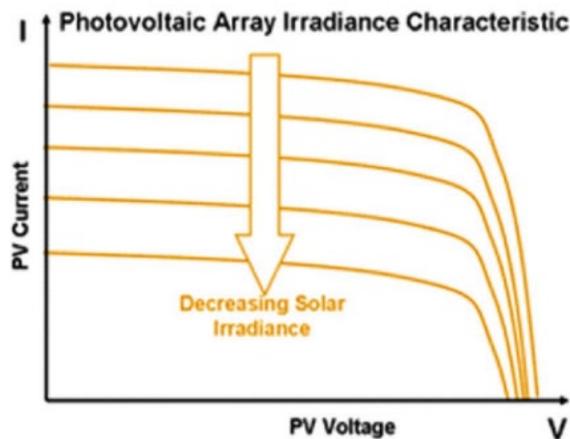


Fig.6 Display Effect of Solar Irradiance [46]

Irradiance is the amount of power that strikes a unit horizontal area within a unit wavelength interval over a unit period of time [51, 52]. Solar irradiance, or solar power, is a key factor influencing panel performance because the solar resource is highly unpredictable [53]. Irradiance typically varies depending on weather conditions, season, geographical location, time of day, and the sun's position

[45]. The sun's position changes throughout the day according to variations in solar altitude [54], as explained in the figure below. Figure 7 presents the global distribution of yearly worldwide horizontal irradiation (GHI) and direct normal irradiation (DNI). The potential of solar resources differs greatly among continents and latitudes [55].

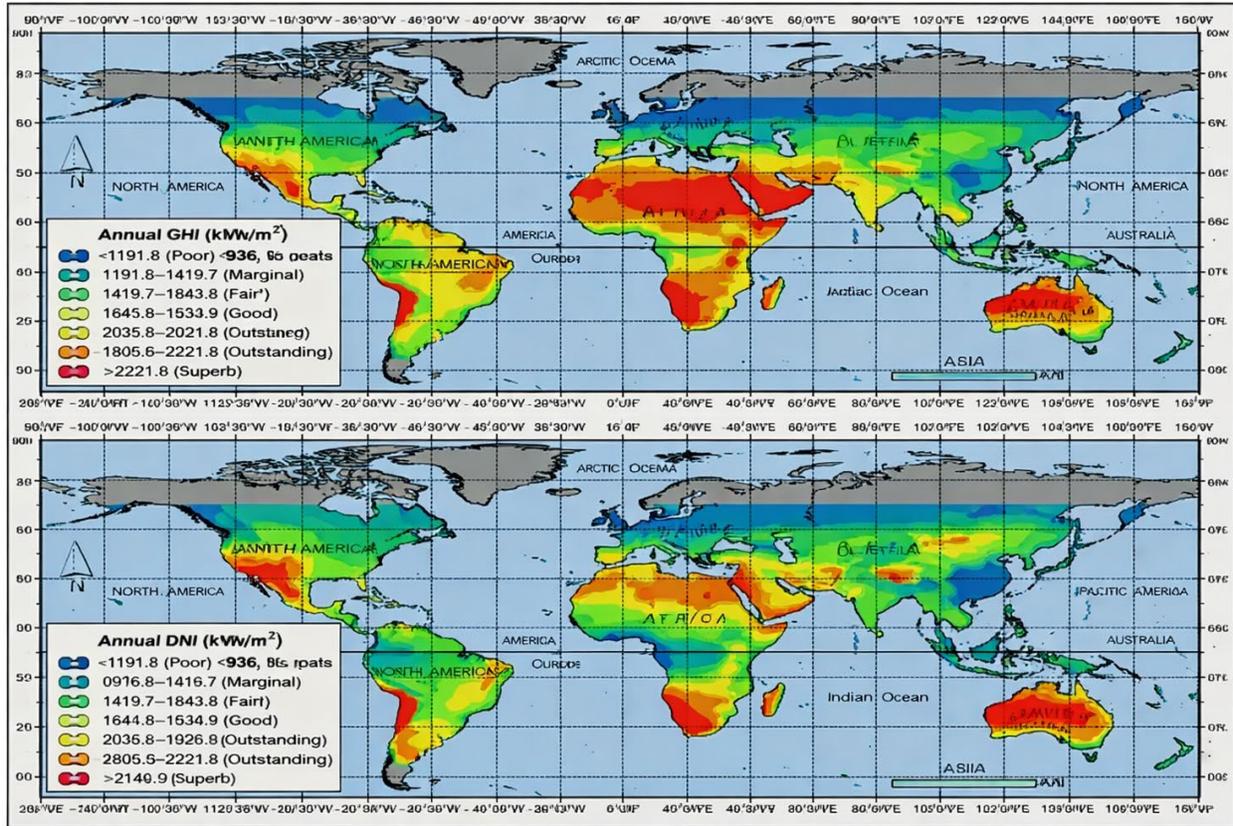


Fig.7 World-Wide Territorial Distribution of Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI)

C. Effect of Wind Speed

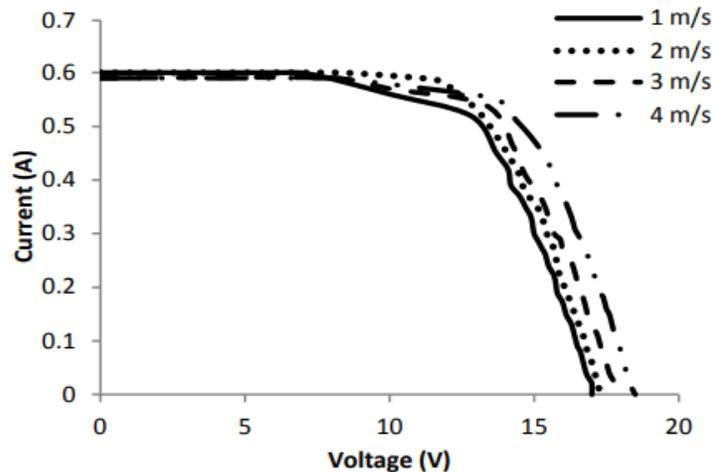


Fig.8 Current-Voltage Characteristics at Different Wind Speeds

Another important factor in boosting PV output is wind speed, which helps cool PV surfaces [43, 56]. This occurs through the reduction of parallel resistance in the PV circuit model [57]. It is not entirely accurate to state that wind velocity directly influences solar PV efficiency; however, it significantly contributes to panel performance. Generally, as wind circulates around the panels, the solar module temperature decreases [58, 59]. The power generated by a photovoltaic module depends on wind conditions, such as wind speed and direction [60]. The most affordable cooling method is natural convective cooling through wind flow [61]. Wind cools solar panels, reducing electron vibration and enabling electrons to move more efficiently to a higher energy state. A solar PV system cooled by 1°C can experience an efficiency increase of approximately 0.05% [46, 62]. The relationship between current and voltage at various wind speeds is depicted in the figure below. At low voltages, the current remains constant, then decreases sharply as it approaches the maximum voltage point [63].

D. Effect of Dust

The temperature rise of a PV panel is caused not only by the ambient climatic temperature but also by direct and indirect partial shading [64]. Photovoltaic panels have been observed to lose up to 85% of their output due to dust, sand, and algae-

like substances that accumulate on their surface; therefore, they must be cleaned periodically to maintain their production levels [65–67]. The performance of PV modules is compromised when sunlight does not fully reach the panel because of dust, atmospheric water vapor, air molecules, and other pollutants. Larger dust particles in the air can scatter sunlight and absorb shorter wavelengths of the incoming solar radiation, leading to reduced solar irradiance [68]. Dust consists of particles of various sizes and compositions. Some dust particles cluster together and adhere to solid surfaces due to ionic charges. Consequently, the force and energy required to remove dust particles may become very high [69, 70]. These variables include the chemical as well as physical characteristics of the dust, along with the size, shape, and weight of the deposited particles, all of which are important in this context. Human activities such as construction, overgrazing, mining, and vehicle transportation significantly increase dust volatility and deposition rates [71, 72].

As explained in Figure 9, there is a relationship between dust density and efficiency reduction. The percentage loss in efficiency increases with dust accumulation, reaching up to 35% at higher dust levels [73]. Table III indicates several factors that may trigger a reduction in PV power output, along with findings from previous studies and the recommended solutions.

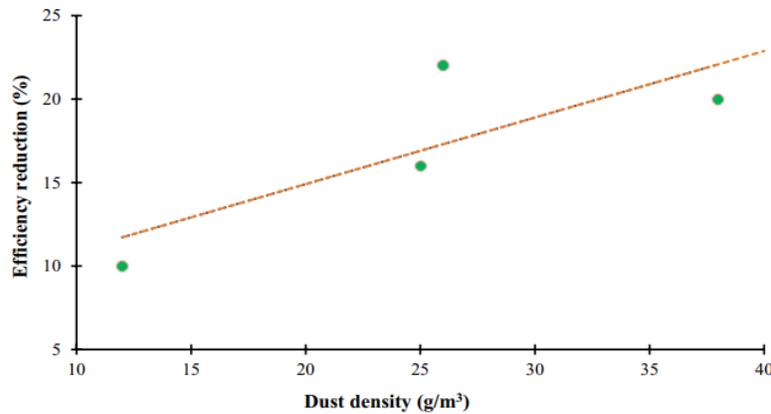


Fig.9 Reduction in Module Efficiency as a Function of Dust Density

TABLE III SHOWS FACTORS AFFECTING PV SYSTEM ALONG WITH SOLUTION

Factors Affecting PV Efficiency	Previous Study Results	Suggestion and Solution	References
Ambient Temperature	Whenever cell operating temperatures go higher, the power output declines down, indicating that the cells are less efficient.	Deploying several cooling technologies to reduce the PV panels surface temperature.	[74]
Sun Irradiance	Simulated PSIM monocrystalline and polycrystalline PV panels work better when the sun is more intense	Greater solar radiation results in higher efficiencies.	[75]
Dirtiness and Dust	Cleanliness is directly associated with the efficiency of a PV panel surface. Dust and other pollutants increase operating temperature, accelerating power loss. Studies report that dust distorts the power output by 8.80% as well as efficiency by 11.86%	An effective cleaning process to recover the energy wasted. Water, detergent, and liquid soap all contribute to a 51 %, 60.1 %, and 68.4 % reduction in the power reduction rate of natural dust, respectively.	[76, 77]

III. COOLING TECHNIQUES

High operating temperatures deteriorate the performance of PV panels. Therefore, it is crucial to introduce an appropriate cooling method to preserve electrical efficiency, reduce surface temperature, and improve module lifespan [43, 78]. Waste heat recovery is becoming an important area of energy management, addressing the large amount of heat loss dictated by the second law of thermodynamics. It minimizes energy waste and environmental degradation, thereby supporting the transition to sustainable energy solutions [79]. Environmental factors such as sunlight intensity, dust, wind, and humidity affect the operating temperature of PV panels; however, these factors cannot be directly controlled in open environments. Nevertheless, cooling techniques provide a stable and economical way to control temperature rise and maintain module performance [43, 80].

Cooling technologies used in PV thermal management are broadly classified into active and passive methods. Passive cooling relies on natural mechanisms, such as air, liquid,

phase change materials (PCMs), and sky radiation, to enhance heat transfer through conduction and convection [81]. Passive techniques can be categorized into three main types: passive air cooling, passive water cooling, and conductive cooling. They may incorporate additional components, such as heat pipes, heat sinks, or heat exchangers, to facilitate natural convection cooling [82]. Active cooling methods, on the other hand, require additional energy to circulate coolants such as air or water. Most active cooling systems are water-based and are commonly used in PV/T (Photovoltaic/Thermal) systems [83]. Figure 10 illustrates various PV module cooling methods, including PCM-based cooling, air cooling, water cooling, and nanofluid cooling techniques [84]. The following table compares passive and active cooling methods of PV modules in terms of ventilation, electrical requirements, heat removal capacity, and cost. Active techniques generally provide higher performance but involve greater investment and maintenance costs than passive techniques [85].

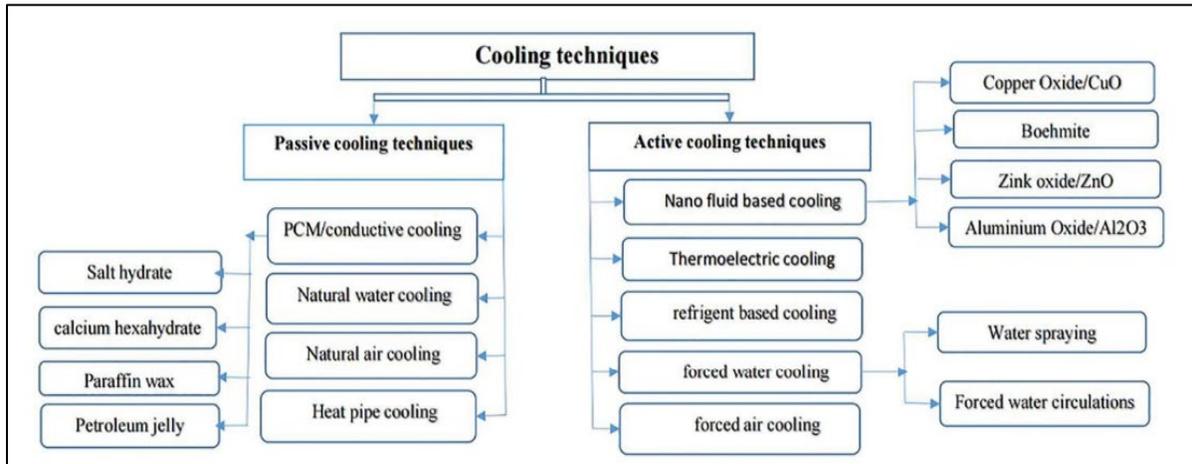


Fig.10 The Major Methods of Cooling are Listed

TABLE IV COMPARISON OF ACTIVE AND PASSIVE PV COOLING SYSTEMS IN TERMS OF PERFORMANCE AND COST

Cooling Methods	Cooling Ways	Electrical Effectiveness	Acquiring Heat	Primary acquisition	Expenses of Service
Passive cooling	Nature Ventilation	☑	☒	☑	☒
	Liquid immersion	☑☑	☒	☑☑	☒
	Heat Pipe	☑☑	☒	☑☑	☒
	PCMs	☑☑☑	☒	☑☑☑☑	☒
Active Cooling	Forced ventilation	☑☑☑	☑☑	☑☑☑	☑☑
	Active liquids (water, nanofluids)	☑☑☑☑	☑☑☑☑	☑☑☑☑	☑☑☑
	Active liquids + PCMs	☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑

Notes: “☒” meaning no or very little, “☑” meaning the lowest and “☑☑☑☑☑” meaning the highest.

A. Natural Ventilation/ Convection

Natural convection occurs due to the circulation of fluids (buoyancy) caused by density differences resulting from temperature variations. When a PV panel becomes hot, the surrounding air warms up, becomes less dense, and rises,

forming a natural convection current that facilitates heat exchange [86]. Natural air cooling is a simple and cost-effective method of cooling PV modules that does not require additional energy. Wind flowing over the panel surface enhances cooling through convection. In rooftop systems, an air gap between the panel and the building allows efficient air

circulation, reducing the average module temperature from 77°C to 39°C [87].

B. Forced Air Cooling

Forced convection involves the use of mechanical devices, such as fans, to move air around PV panels more rapidly. This helps dissipate heat more effectively than natural convection. Panel efficiency is maximized by maintaining lower operating temperatures [88]. It may involve the installation of fans, air ducts, or a combination of heat exchangers [89]. This cooling method is based on the forced circulation of air over the front and back surfaces of PV panels, but it requires significant fan energy [90]. Forced convection through active ventilation can increase electrical output by up to 8% [91].

C. Liquid based cooling

The concept of using water to cool PV modules has existed since the late 1960s [92]. Water cooling is an effective method for enhancing PV performance because water has a high heat absorption capacity [93]. It improves temperature control and system efficiency and can be implemented as either a passive or active cooling method, depending on specific requirements [62]. Currently, this cooling approach is widely researched and optimized, contributing to improved efficiency in solar power generation systems. Natural water cooling, water spraying, forced water circulation, and nanofluid-based cooling techniques are common methods of water cooling [84, 94].

1. Forced Water cooling: PV modules have heat pipes installed on the reverse side of the modules to dissipate heat to a circulating coolant, thereby minimizing cell temperature [95]. Although effective, the system's efficiency depends largely on the thermal conductivity of the material used for

the pipes. However, this technique is not suitable for large-scale solar plants due to the high installation and material costs [96].

2. Liquid immersion cooling: The immersion cooling procedure involves installing PV panels in water. The surrounding water absorbs heat from the solar panels, resulting in improved efficiency [97]. When submerged in water to a depth of 1 cm, electrical efficiency can be enhanced by up to 17.8%. Although this method has minimal environmental impact and significant temperature reduction potential, it cannot be applied to floating solar systems [98].

D. Thermoelectric Cooling

Thermoelectric modules (TEMs) provide a viable means of optimizing PV performance by removing excess heat. A thermoelectric cooler (TEC) operates on the principle that a temperature difference can be generated in proportion to the current flowing through the device; thus, a TEC can enhance heat rejection and overall module efficiency when operated with a DC current [99, 100].

A temperature difference across a thermoelectric module (TEM) can also be utilized through the Seebeck effect in a thermoelectric generator (TEG). TEGs are highly suitable for recovering and utilizing thermal losses, thereby increasing power production by converting the module's residual heat into electricity [101].

The relationship between thermoelectric input voltage and the hot- and cold-side temperatures of the module is depicted in the figure below. An increase in input voltage raises the hot-side temperature and lowers the cold-side temperature, thereby enhancing the cooling effect [99].

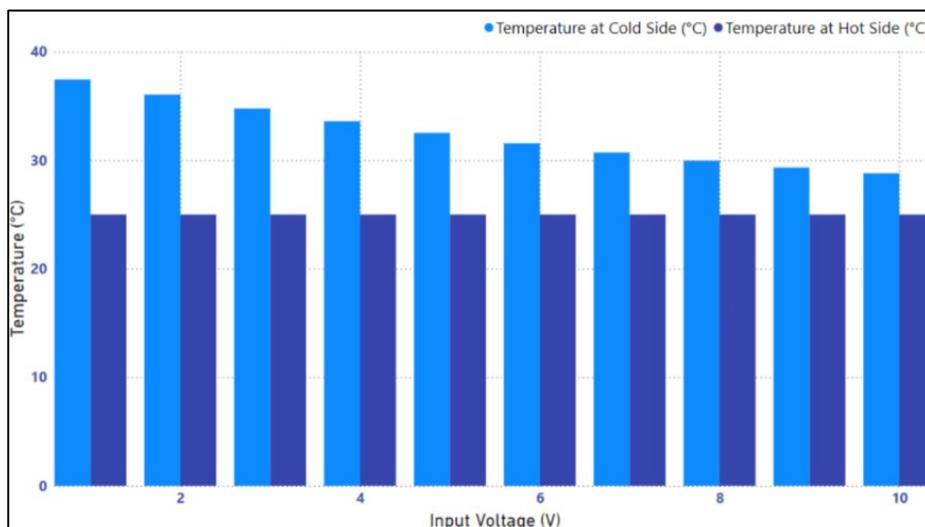


Fig.11 Effect of Input Voltage on the Cooling of TEC

E. Application of Phase Change Material (PCM) in cooling

PCMs are a group of substances capable of changing between solid and liquid phases within a specific temperature range and vice versa [102]. PCMs possess a high latent heat of

fusion, meaning they absorb and release significant amounts of heat during melting and solidification at certain temperatures [103]. They can store and release large amounts of thermal energy [104].

In recent years, scholars have focused on PCM-based approaches for PV thermal control [105]. A PV-PCM system is a hybrid technology that integrates PV panels and PCMs into a single module to enhance solar energy conversion efficiency [106]. Thermal energy storage (TES) using PCMs involves the storage and release of latent and sensible heat. PCMs emerged as a high-priority energy management method following the 1973–1974 energy crisis. In the current context of declining fossil fuel reserves and growing concerns about greenhouse gas emissions, energy consumption has become a critical issue. PCM-based TES

offers a practical and effective approach to improving energy efficiency in various domestic and industrial applications [107–109]. PCMs are classified as organic, inorganic, or eutectic based on their chemical nature and phase-change behavior [110]. Organic PCMs include paraffins, fatty acids, and glycols, while inorganic PCMs consist of salt hydrates and metals. Eutectic mixtures combine different types of PCMs to achieve customized melting properties [111], as illustrated in Figure 12 below. The selection of PCM for PV integration is guided by its favorable properties, as illustrated in Table V.

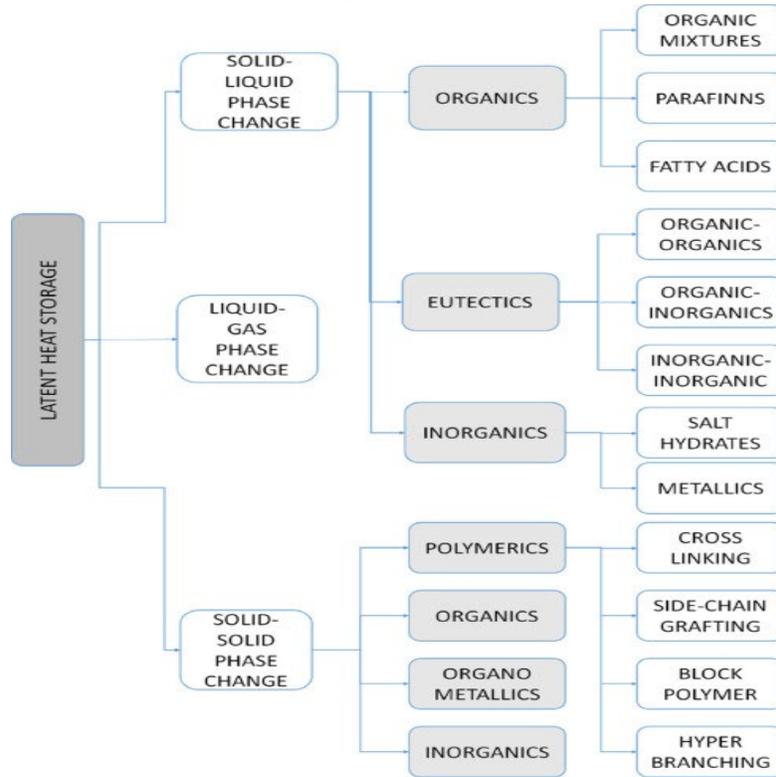


Fig.12 Classification of Various PCM According to their Nature [112]

TABLE V DEFINES VARIOUS PROPERTIES OF DIFFERENT PCM [113]

Organic	Inorganic	Eutectics
They consist of long chains of hydrogen and carbon molecules and include paraffin (C _n H _{2n}) and are also known as polymers	High fusion heat	High melting point
Not in the supercooling category	High thermal conductivity	High thermal capacity volume storage
Available in an extensive temperature range.	Low change in volume	Expensive
Stable both chemically and physically	Easily accessible	Limited availability of property data
A high fusion heat	Noncombustible	-
Ability to melt congruently	Supercooling	-
Combustible	Cause corrosion	-
low intensity of volumetric energy	Not melting uniformly	-
Exhibits low thermal conductivity	Excessive intensity of volumetric energy	-

PV-PCM systems have become a popular research topic in the field of passive cooling, aiming to reduce cell temperature and improve efficiency without the use of fluids or external power. However, their practical application remains limited

due to certain drawbacks of PCMs, including low thermal conductivity, leakage issues, high cost, and limited storage capacity. These challenges must be addressed through critical evaluation of recent advancements to enhance system

reliability [113]. A photovoltaic panel captures solar irradiance and converts it into electrical energy. The figure shows a simple arrangement of PV modules under sunlight [114]. A PCM initially heats sensibly to its melting temperature, then absorbs latent heat and undergoes a phase transition at approximately constant temperature. The time required for this process depends on the mass of the PCM, its thermal conductivity, and heat transfer enhancement mechanisms. Once fully melted, the material returns to sensible heating [115].

The two primary factors used to identify an appropriate PCM are its melting temperature and latent heat. The figure below describes PCMs with respect to their melting temperatures [116]. The technology utilizes the unique thermal characteristics of PCMs to absorb and store excess heat generated during the operation of PV panels, thereby helping to control panel temperature and enhance performance and lifespan under various climatic conditions [117]. A PV-PCM

panel operates at a lower temperature than a conventional PV panel and thus improves the overall efficiency of the system [118].

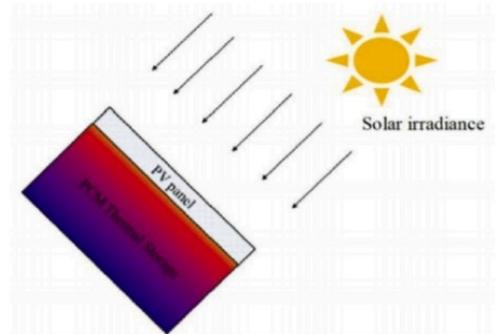


Fig.13 Shows Schematic of PV Attached with PCM

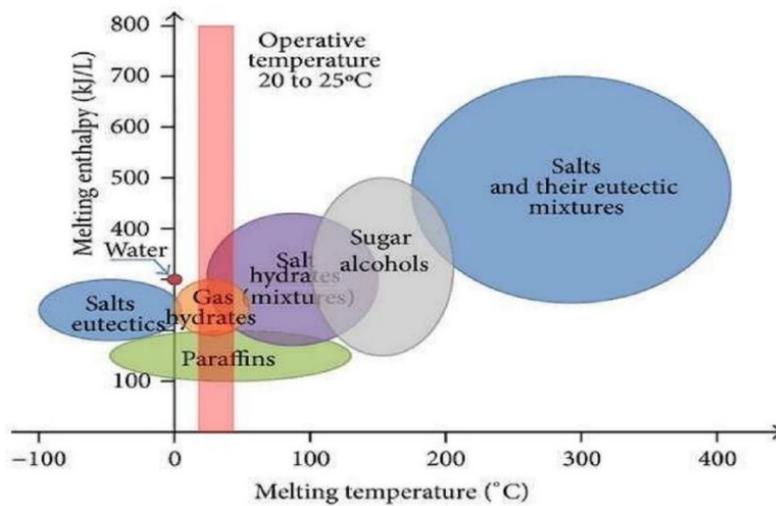


Fig.14 Commonly Used PCM and its Melting Temperature

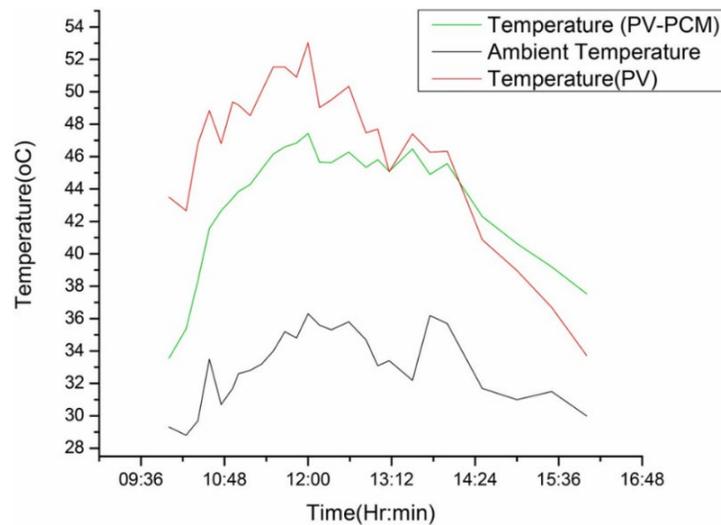


Fig.15 Effect of PCM on PV temperature

The amount of solar radiation incident on PV panels fluctuates throughout the day, affecting their performance. Figure 16 shows that PV-PCM panels (with 3 cm PCM thickness) consistently perform better than standard panels at all tilt angles. The PV-PCM panel achieves an efficiency of

14.36% at a 30° tilt and 800 W/m², whereas standard panels reach only 13.1% efficiency. Both types of panels perform best at a 30° tilt; however, the improvement provided by PCM becomes limited as the radiation level increases [119].

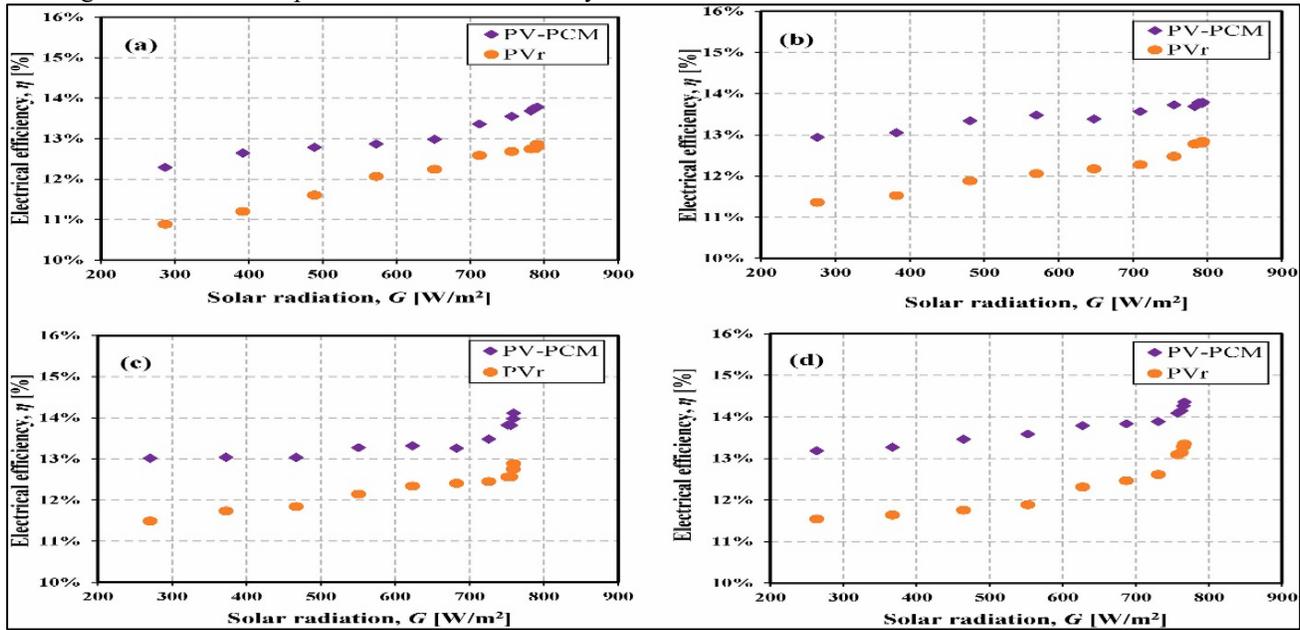


Fig.16 Comparison of Electrical Efficiency and Solar Radiation Between Pvr and PV-PCM Panels with a 3 Cm PCM Thickness at Tilt Angle of (A) 15° (B) 20° (C) 25° (D) 30°

IV. FUTURE RESEARCH DIRECTIONS

More research is necessary to enhance the thermal conductivity of phase change materials (PCMs) to improve their effectiveness in photovoltaic (PV) cooling systems. Nanostructured PCMs and advanced composites may significantly increase heat transfer while preserving latent heat storage capacity. Hybrid cooling methods, such as combining PCM with liquid cooling or thermoelectric modules, have great potential to improve thermal regulation efficiency and overall power output. Long-term experiments under real climatic conditions are required to assess durability, reliability, and practical viability. Field testing and evaluation should examine performance degradation, material integrity, and maintenance requirements, in addition to comprehensive techno-economic and life-cycle analyses to determine large-scale feasibility. Future developments should focus on smart thermal management systems with real-time optimization, integrating IoT sensors and artificial intelligence-based control. Additionally, improved encapsulation techniques are needed to prevent PCM leakage, and standardized evaluation criteria should be established to enable consistent comparisons of cooling technologies across different climatic conditions.

V. CONCLUSION

This review has addressed the major environmental and operational factors influencing photovoltaic (PV) systems, such as ambient temperature, solar irradiance, wind speed, and dust accumulation. Among these, high module

temperature is the most critical, as it significantly reduces electrical efficiency and accelerates material degradation. Other factors affecting performance include dust deposition and fluctuations in irradiance, highlighting the need for effective thermal and environmental control measures. Various cooling techniques have been discussed, including passive methods such as natural ventilation and PCM integration, and active methods such as forced air cooling, liquid-based cooling, and thermoelectric cooling. Passive methods offer advantages such as simplicity and low operating costs, whereas active methods provide greater temperature reduction but involve higher complexity and energy consumption. The selection of an appropriate cooling technique depends on climatic conditions, economic feasibility, and the scale of system installation. Overall, proper thermal management plays a crucial role in enhancing PV reliability, energy yield, and module lifespan, thereby increasing the contribution of solar energy to sustainable electricity generation.

ACKNOWLEDGEMENT

The authors are grateful to Xi'an Jiaotong University, China, for providing the opportunity to undertake this research work.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Use of Artificial Intelligence (AI)-Assisted Technology for Manuscript Preparation

The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

ORCID

Zulqarnain Hyder  <https://orcid.org/0009-0009-5414-1566>
 Shahzaib Ali  <https://orcid.org/0009-0002-5917-6740>
 Ghulam Mujataba  <https://orcid.org/0009-0007-9381-2153>
 Zaheer Uddin  <https://orcid.org/0009-0006-6363-9559>
 Zaryab Basharat  <https://orcid.org/0009-0008-1914-3331>
 Muhammad Shoaib  <https://orcid.org/0009-0000-9579-4015>

REFERENCES

- [1] B. Freedman, W. Dorsey, A. Frazier, M. Kambhampati, J. Galiotos, and S. J. E. S. Mukherjee, "Renewable and non-renewable energy sources," 2024.
- [2] S. Chandel and T. Agarwal, "Review of cooling techniques using phase change materials for enhancing efficiency of photovoltaic power systems," *Renewable and Sustainable Energy Reviews*, vol. 73, pp. 1342–1351, 2017.
- [3] Z. Hyder *et al.*, "Experimental evaluation of torrefied sawdust pellets as a potential solid fuel in Pakistan," vol. 14, no. 2, pp. 39–48, 2025.
- [4] A. K. Hamzat, A. Z. Sahin, M. I. Omisanya, and L. M. Alhems, "Advances in PV and PVT cooling technologies: A review," *Sustainable Energy Technologies and Assessments*, vol. 47, p. 101360, 2021.
- [5] S. I. Seneviratne *et al.*, "Weather and climate extreme events in a changing climate," pp. 1513–1766, 2021.
- [6] M. Khaled, F. Harambat, and H. Peerhossaini, "Towards the control of car underhood thermal conditions," *Applied Thermal Engineering*, vol. 31, no. 5, pp. 902–910, 2011.
- [7] H. Bagdadee *et al.*, "A review on hybrid energy generation: Cow dung biogas, solar thermal and kinetic energy integration for power production," *Energy and Built Environment*, vol. 6, no. 1, pp. 109–120, 2025.
- [8] S. Preet *et al.*, "Energy characterization of forced ventilated photovoltaic-DSF system in hot summer of composite climate," *Energy and Built Environment*, vol. 5, no. 5, pp. 704–718, 2024.
- [9] R. Jayabal, "Towards a carbon-free society: Innovations in green energy for a sustainable future," *Renewable Energy*, vol. 24, p. 103121, 2024.
- [10] K. Faraj *et al.*, "Analysis of underfloor electrical heating system integrated with coconut oil-PCM plates," *Applied Thermal Engineering*, vol. 158, p. 113778, 2019.
- [11] H. Jaber, M. Ramadan, and M. Khaled, "Domestic thermoelectric cogeneration system optimization analysis, energy consumption and CO₂ emissions reduction," *Applied Thermal Engineering*, vol. 130, pp. 279–295, 2018.
- [12] M. W. Akram *et al.*, "Global technological advancement and challenges of glazed window, facade system and vertical greenery-based energy savings in buildings: A comprehensive review," *Energy and Built Environment*, vol. 4, no. 2, pp. 206–226, 2023.
- [13] R. El Kassar *et al.*, "Phase change materials for enhanced photovoltaic panels performance: A comprehensive review and critical analysis," *Energy and Built Environment*, vol. 6, no. 4, pp. 655–675, 2025.
- [14] Chaudhuri *et al.*, "Energy conversion strategies for wind energy system: Electrical, mechanical and material aspects," *Materials*, vol. 15, no. 3, p. 1232, 2022.
- [15] M. Dada and P. Popoola, "Recent advances in solar photovoltaic materials and systems for energy storage applications: A review," *Benue State University Journal of Basic and Applied Sciences*, vol. 12, no. 1, pp. 1–15, 2023.
- [16] S. J. Chantasiriwan, "Comparison between two solar feed water heating systems in thermal power plant," *Int. J. Thermodynamics*, vol. 15, p. 100167, 2022.
- [17] K. Zhang, "A review of biomass energy: Comparison of utilization methods and future prospects," in *E3S Web of Conferences*, vol. 606, p. 05007, 2025.
- [18] P. S. Deora, Y. Verma, R. A. Muhal, C. Goswami, and T. P. Singh, "Biofuels: An alternative to conventional fuel and energy source," *Materials Today: Proceedings*, vol. 48, pp. 1178–1184, 2022.
- [19] D. S. Ion and A. Zapciu, "Research on the implementation of the hydrogen and oxygen-based fuel cell renewable energy source," *Int. J. Modern Mechanics*, no. 15, pp. 120–126, 2024.
- [20] M. M. Ahmad, A. Kumar, and R. Ranjan, "Recent developments of tidal energy as renewable energy: An overview," *Coastal Engineering: Hydraulics and Coastal Engineering*, pp. 329–343, 2022.
- [21] H. Hassan, "Fundamentals of geothermal energy extraction," in *Utilization of Thermal Potential of Abandoned Wells*. Elsevier, 2022, pp. 11–33.
- [22] T. Thennakoon *et al.*, "Harnessing the power of ocean energy: A comprehensive review of power generation technologies and future perspectives," vol. 4, no. 3, pp. 73–102, 2023.
- [23] S. Yadav, P. Jain, and P. Singh, "Solar energy concentrator research: Past and present," *Solar Energy Conversion and Applications*, pp. 121–136, 2024.
- [24] X. Sun, S. Jiang, H. Huang, H. Li, B. Jia, and T. Ma, "Solar energy catalysis," *Angewandte Chemie*, vol. 134, no. 29, p. e202204880, 2022.
- [25] S. N. Vodapally and M. H. Ali, "A comprehensive review of solar photovoltaic (PV) technologies, architecture, and its applications to improved efficiency," *Energies*, vol. 16, no. 1, p. 319, 2022.
- [26] L. Panagoda *et al.*, "Advancements in photovoltaic (PV) technology for solar energy generation," vol. 4, no. 3, pp. 30–72, 2023.
- [27] M. Hasan *et al.*, "Harnessing solar power: A review of photovoltaic innovations, solar thermal systems, and the dawn of energy storage solutions," *Energies*, vol. 16, no. 18, p. 6456, 2023.
- [28] N. S. M. N. Izam, Z. Itam, W. L. Sing, and A. Syamsir, "Sustainable development perspectives of solar energy technologies with focus on solar photovoltaic—A review," *Energies*, vol. 15, no. 8, p. 2790, 2022.
- [29] K. Pandey, R. Kumar, and M. Samykano, "Solar energy: Direct and indirect methods to harvest usable energy," in *Dye-Sensitized Solar Cells*. Elsevier, 2022, pp. 1–24.
- [30] S. Singh, P. Singh, and Z. Said, "Solar energy applications," 2023, pp. 1–23.
- [31] B. Desalegn, D. Gebeyehu, and B. Tamrat, "Wind energy conversion technologies and engineering approaches to enhancing wind power generation: A review," vol. 8, no. 11, 2022.
- [32] S. W. Glunz, R. Preu, and D. Biro, "Crystalline silicon solar cells: State-of-the-art and future developments," *Comprehensive Renewable Energy*, vol. 1, pp. 353–387, 2012.
- [33] K. Khan and M. A. Salek, "Solar photovoltaic (SPV) conversion: A brief study," vol. 5, no. 5, pp. 187–204, 2019.
- [34] J. Pastuszak and P. Wegierek, "Photovoltaic cell generations and current research directions for their development," *Materials*, vol. 15, no. 16, p. 5542, 2022.
- [35] M. M. Musztyfaga-Staszuk and C. Mele, "Structural and electrical analysis of crystalline silicon solar cells: The role of busbar geometry in first-generation PV technology," *Materials*, vol. 18, no. 21, p. 4979, 2025.
- [36] V. H. U. Eze, K. Richard, K. J. Ukagwu, and W. Okafor, "Factors influencing the efficiency of solar energy systems," *J. Energy Technology and Science*, vol. 6, no. 3, pp. 119–131, 2024.
- [37] T. Ma, H. Yang, Y. Zhang, L. Lu, and X. Wang, "Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: A review and outlook," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 1273–1284, 2015.
- [38] N. F. Voudoukis, "Photovoltaic technology and innovative solar cells," *European Journal of Engineering and Science*, vol. 2, no. 1, 2018.
- [39] J. A. Luceño-Sánchez, A. M. Díez-Pascual, and R. Peña Capilla, "Materials for photovoltaics: State of art and recent developments," *Int. J. Mol. Sci.*, vol. 20, no. 4, p. 976, 2019.
- [40] V. Tan, P. R. Dias, N. Chang, and R. Deng, "Estimating the lifetime of solar photovoltaic modules in Australia," *Sustainability*, vol. 14, no. 9, p. 5336, 2022.
- [41] J. Siecker, K. Kusakana, and B. P. Numbi, "A review of solar photovoltaic systems cooling technologies," *Renewable and Sustainable Energy Reviews*, vol. 79, pp. 192–203, 2017.
- [42] Y. Shen, M. Fouladirad, and A. Grall, "Impact of dust and temperature on photovoltaic panel performance: A model-based approach to determine optimal cleaning frequency," vol. 10, no. 16, 2024.

- [43] E. M. H. Ismaeil and M. U. Farooq, "Review of cooling techniques for improving solar photovoltaic panel efficiency," vol. 125, no. 1, pp. 193–219, 2025.
- [44] S. A. A. Dos Santos *et al.*, "The impact of aging of solar cells on the performance of photovoltaic panels," *Energy Conversion and Management: X*, vol. 10, p. 100082, 2021.
- [45] K. Hasan *et al.*, "Effects of different environmental and operational factors on the PV performance: A comprehensive review," vol. 10, no. 2, pp. 656–675, 2022.
- [46] P. Dwivedi, K. Sudhakar, A. Soni, E. Solomin, and I. Kirpichnikova, "Advanced cooling techniques of PV modules: A state of art," *Case Studies in Thermal Engineering*, vol. 21, p. 100674, 2020.
- [47] M. Abou Akrouh *et al.*, "Advancements in cooling techniques for enhanced efficiency of solar photovoltaic panels: A detailed comprehensive review and innovative classification," vol. 6, no. 2, pp. 248–276, 2025.
- [48] W. S. Ebhota and T.-C. Jen, "Photovoltaic solar energy: Potentials and outlooks," in *ASME Int. Mechanical Engineering Congress and Exposition*, vol. 52088, p. V06BT08A028, 2018.
- [49] F. Shaik, S. S. Lingala, and P. Veeraboina, "Effect of various parameters on the performance of solar PV power plant: A review and the experimental study," *Scientific Reports*, vol. 10, no. 1, p. 6, 2023.
- [50] W. Ebhota and P. Tabakov, "Influence of photovoltaic cell technologies and elevated temperature on photovoltaic system performance," *Applied Sciences*, vol. 14, no. 7, p. 101984, 2023.
- [51] H. I. Aouidat and A. Bouhelal, "Machine learning-based short-term solar power forecasting: A comparison between regression and classification approaches using extensive Australian dataset," vol. 11, no. 1, p. 28, 2024.
- [52] R. Santbergen *et al.*, "Calculation of irradiance distribution on PV modules by combining sky and sensitivity maps," *Solar Energy*, vol. 150, pp. 49–54, 2017.
- [53] T. C. Carneiro *et al.*, "Review on photovoltaic power and solar resource forecasting: Current status and trends," *Journal of Solar Energy Engineering*, vol. 144, no. 1, p. 010801, 2022.
- [54] M. Fouad, L. A. Shihata, and E. I. Morgan, "An integrated review of factors influencing the performance of photovoltaic panels," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 1499–1511, 2017.
- [55] R. Práválie, C. Patriche, and G. Bandoc, "Spatial assessment of solar energy potential at global scale: A geographical approach," *Journal of Cleaner Production*, vol. 209, pp. 692–721, 2019.
- [56] M. Mehdi *et al.*, "Experimental investigation on the effect of wind as a natural cooling agent for photovoltaic power plants in desert locations," *Case Studies in Thermal Engineering*, vol. 47, p. 103038, 2023.
- [57] E. Kaplani and S. Kaplanis, "Thermal modelling and experimental assessment of the dependence of PV module temperature on wind velocity and direction, module orientation and inclination," *Solar Energy*, vol. 107, pp. 443–460, 2014.
- [58] J. K. Kaldellis, M. Kapsali, and K. A. Kavadias, "Temperature and wind speed impact on the efficiency of PV installations: Experience obtained from outdoor measurements in Greece," *Renewable Energy*, vol. 66, pp. 612–624, 2014.
- [59] J. F. de F. Filho, W. L. Neves, and F. B. Costa, "Photovoltaic module temperature prediction model incorporating wind direction and precipitation effects," *Int. J. Photoenergy*, 2025.
- [60] L. Xinyue, M. Wenyong, L. Haiyun, and C. Wenkao, "Experimental study on wind-induced vibration characteristics of flexible photovoltaic array," *Applied Acoustics and Structures*, vol. 43, no. 4, pp. 118–128, 2025.
- [61] Vassel and F. J. E. Iakovidis, "The effect of wind direction on the performance of solar PV plants," *Energy Conversion and Management*, vol. 153, pp. 455–461, 2017.
- [62] M. Sharaf, M. S. Yousef, and A. S. Huzayyin, "Review of cooling techniques used to enhance the efficiency of photovoltaic power systems," *Environmental Science and Pollution Research*, vol. 29, no. 18, pp. 26131–26159, 2022.
- [63] M. J. Al-Maghalseh and I. Engineering, "Experimental study to investigate the effect of dust, wind speed and temperature on the PV module performance," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 12, no. 2, 2018.
- [64] N. Kushwaha, V. K. Yadav, and R. Saha, "Effect of partial shading on photovoltaic systems performance and its mitigation techniques—A review," *Environmental Science and Pollution Research*, vol. 45, no. 4, pp. 11155–11180, 2023.
- [65] S. A. Sulaiman, A. K. Singh, M. M. M. Mokhtar, and M. A. Bou-Rabee, "Influence of dirt accumulation on performance of PV panels," *Energy Procedia*, vol. 50, pp. 50–56, 2014.
- [66] G. Vedulla and A. Geetha, "Dust accumulation on solar photovoltaic panels: An investigation study on power loss and efficiency reduction," *The Scientific World Journal*, vol. 27, no. 4, pp. 2967–2976, 2023.
- [67] C. O. Rusănescu, M. Rusănescu, I. A. Istrate, G. A. Constantin, and M. Begea, "The effect of dust deposition on the performance of photovoltaic panels," *Energies*, vol. 16, no. 19, p. 6794, 2023.
- [68] M. Mani and R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 3124–3131, 2010.
- [69] M. Altıntaş and S. Arslan, "The study of dust removal using electrostatic cleaning system for solar panels," *Sustainability*, vol. 13, no. 16, p. 9454, 2021.
- [70] M. Nezamisavjbolaghi, E. Davodian, A. Bouich, M. Tlemçani, O. Mesbahi, and F. M. Janeiro, "The impact of dust deposition on PV panels' efficiency and mitigation solutions," *Energies*, vol. 16, no. 24, p. 8022, 2023.
- [71] R. Appels *et al.*, "Effect of soiling on photovoltaic modules," *Solar Energy*, vol. 96, pp. 283–291, 2013.
- [72] M. R. Maghami, "Impact of dust deposition on photovoltaic systems and mitigation strategies," *Technologies*, vol. 14, no. 1, p. 15, 2025.
- [73] H. Jiang, L. Lu, and K. Sun, "Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules," *Atmospheric Environment*, vol. 45, no. 25, pp. 4299–4304, 2011.
- [74] K. Natesan, C. K. Nagaraj, and N. K. Chandran, "Studies on improvement of solar PV panel performance," *Journal of Chemical Technology and Metallurgy*, vol. 58, no. 6, pp. 1065–1070, 2023.
- [75] Genc, A. Karakilic, and N. Karafil, "Effects of temperature and solar irradiation on performance of monocrystalline, polycrystalline, and thin-film PV panels," *International Journal of Thermophysics*, vol. 51, pp. 254–260, 2022.
- [76] M. T. Chaichan and H. A. Kazem, "Experimental evaluation of dust composition impact on photovoltaic performance in Iraq," *Environmental Science and Pollution Research*, vol. 46, no. 1, pp. 7018–7039, 2024.
- [77] R. J. Mustafa, M. R. Gomaa, M. Al-Dhaifallah, and H. Rezk, "Environmental impacts on the performance of solar photovoltaic systems," *Sustainability*, vol. 12, no. 2, p. 608, 2020.
- [78] V. Kumar *et al.*, "Enhancing solar photovoltaic system efficiency: Recent progress on its cooling techniques," *Renewable Energy*, vol. 45, no. 8, p. 113, 2024.
- [79] Y. Zhang *et al.*, "A novel porous channel to optimize the cooling performance of PV modules," *Journal of Energy Storage*, vol. 3, no. 2, pp. 210–225, 2022.
- [80] Z. Peng, M. R. Herfatmanesh, and Y. Liu, "Cooled solar PV panels for output energy efficiency optimisation," *Energy Conversion and Management*, vol. 150, pp. 949–955, 2017.
- [81] D. H. El-Nagar, M. Emam, A. El-Betar, and S. A. Nada, "Combining active and passive cooling techniques for maximizing power generation and thermal utilization of photovoltaic panels," *Renewable Energy*, vol. 250, p. 123310, 2025.
- [82] E. Kozłowska and M. Szkodo, "Contemporary and conventional passive methods of intensifying convective heat transfer—A review," *Energies*, vol. 17, no. 17, p. 4268, 2024.
- [83] S. Xu, H. Zhang, and Z. Wang, "Thermal management and energy consumption in air, liquid, and free cooling systems for data centers: A review," *Energies*, vol. 16, no. 3, p. 1279, 2023.
- [84] T. A. Takiso and B. T. Manbecho, "Recent improvements of the PV solar energy generation performance," *International Journal of Recent Technology and Engineering*, vol. 10, no. 3, pp. 117–129, 2021.
- [85] T. Ma, Z. Li, and J. Zhao, "Photovoltaic panel integrated with phase change materials (PV-PCM): Technology overview and materials selection," *Renewable and Sustainable Energy Reviews*, vol. 116, p. 109406, 2019.
- [86] T. Ibrahim *et al.*, "Cooling techniques for enhanced efficiency of photovoltaic panels—Comparative analysis with environmental and economic insights," *Energies*, vol. 17, no. 3, p. 713, 2024.

- [87] S. A. Kalogirou, L. Aresti, P. Christodoulides, and G. Florides, "The effect of air flow on a building integrated PV-panel," *Progress in Industrial Ecology*, vol. 11, pp. 89–97, 2014.
- [88] Hussien, A. Eltayesh, and H. M. El-Batsh, "Experimental and numerical investigation for PV cooling by forced convection," *Alexandria Engineering Journal*, vol. 64, pp. 427–440, 2023.
- [89] R. Rebhi *et al.*, "Forced-convection heat transfer in solar collectors and heat exchangers: A review," *Journal of Advanced Research in Applied Sciences and Engineering Technology*, vol. 26, no. 3, pp. 1–15, 2022.
- [90] D. Li, M. King, M. Dooner, S. Guo, and J. Wang, "Study on the cleaning and cooling of solar photovoltaic panels using compressed airflow," *Solar Energy*, vol. 221, pp. 433–444, 2021.
- [91] S. Krauter *et al.*, "Combined photovoltaic and solar thermal systems for facade integration and building insulation," *Solar Energy*, vol. 67, no. 4–6, pp. 239–248, 1999.
- [92] D. Cotfas and P. Cotfas, "Multiconcept methods to enhance photovoltaic system efficiency," *International Journal of Photoenergy*, vol. 2019, no. 1, p. 1905041, 2019.
- [93] E. Alrashedy, H. S. Abdelmohsen, A. R. Abdelrahman, and S. Abdelhady, "A review paper: Enhancement of the performance of PV systems by evaporative and water-cooling methods," *International Journal of Ambient Energy*, vol. 7, no. 2, pp. 21–35, 2025.
- [94] K. Mostakim, M. R. Akbar, M. A. Islam, and M. K. Islam, "Integrated photovoltaic-thermal system utilizing front surface water cooling technique: An experimental performance response," *Heliyon*, vol. 10, no. 3, 2024.
- [95] S. Ahmed, S. Li, Z. Li, G. Xiao, and T. Ma, "Enhanced radiative cooling of solar cells by integration with heat pipe," *Applied Energy*, vol. 308, p. 118363, 2022.
- [96] K. Singh and R. Kumar, "Enhancing renewable energy systems using loop heat pipes: A case research on solar thermal applications," *Applied Thermal Engineering*, vol. 275, p. 126866, 2025.
- [97] Wang, F. Guo, H. Liu, and G. Wang, "A comprehensive review of research works on cooling methods for solar photovoltaic panels," *Energies*, vol. 18, no. 16, p. 4305, 2025.
- [98] S. Mehrotra, P. Rawat, M. Debbarma, and K. Sudhakar, "Performance of a solar panel with water immersion cooling technique," *International Journal of Science, Environment and Technology*, vol. 3, no. 3, pp. 1161–1172, 2014.
- [99] M. Faheem, M. Abu Bakr, M. Ali, M. A. Majeed, Z. M. Haider, and M. O. Khan, "Evaluation of efficiency enhancement in photovoltaic panels via integrated thermoelectric cooling and power generation," *Energies*, vol. 17, no. 11, p. 2590, 2024.
- [100] S. Shoeibi, H. Kargarsharifabad, M. Sadi, A. Arabkoohsar, and S. A. A. Mirjalily, "A review on using thermoelectric cooling, heating, and electricity generators in solar energy applications," *Sustainable Energy Technologies and Assessments*, vol. 52, p. 102105, 2022.
- [101] G. Contento, B. Lorenzi, A. Rizzo, and D. Narducci, "Efficiency enhancement of a-Si and CZTS solar cells using different thermoelectric hybridization strategies," *Energy*, vol. 131, pp. 230–238, 2017.
- [102] F. Chebli and F. Mechighel, "Phase change materials: Classification, use, phase transitions, and heat transfer enhancement techniques—A comprehensive review," *Journal of Thermal Analysis and Calorimetry*, vol. 150, no. 3, pp. 1353–1411, 2025.
- [103] G. Murali *et al.*, "Improved solar still productivity using PCM and nano-PCM composites integrated energy storage," *Scientific Reports*, vol. 14, no. 1, p. 15609, 2024.
- [104] Surya, R. Prakash, and N. Nallusamy, "Heat transfer enhancement and performance study on latent heat thermal energy storage system using different configurations of spherical PCM balls," *Journal of Energy Storage*, vol. 72, p. 108643, 2023.
- [105] K. Jiao, L. Lu, L. Zhao, and G. Wang, "Towards passive building thermal regulation: A state-of-the-art review on recent progress of PCM-integrated building envelopes," *Sustainability*, vol. 16, no. 15, p. 6482, 2024.
- [106] D. Singh, H. Chaubey, Y. Parvez, A. Monga, and S. Srivastava, "Performance improvement of solar PV module through hybrid cooling system with thermoelectric coolers and phase change material," *Solar Energy*, vol. 241, pp. 538–552, 2022.
- [107] M. K. Rathod and J. Banerjee, "Thermal stability of phase change materials used in latent heat energy storage systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 18, pp. 246–258, 2013.
- [108] Nandi *et al.*, "A comprehensive review on enhanced phase change materials (PCMs) for high-performance thermal energy storage: Progress, challenges, and future perspectives," *Journal of Materials Chemistry A*, vol. 150, no. 12, pp. 8933–8976, 2025.
- [109] Liu, H. Xie, Z. Wu, and Y. Wang, "Advances and outlook of TE-PCM system: A review," *Clean Energy*, vol. 1, no. 1, p. 20, 2022.
- [110] H. Mehling, "Review of classification of PCMs, with a focus on the search for new, suitable PCM candidates," *Energies*, vol. 17, no. 17, p. 4455, 2024.
- [111] N. Elias and V. N. Stathopoulos, "A comprehensive review of recent advances in materials aspects of phase change materials in thermal energy storage," *Energy Procedia*, vol. 161, pp. 385–394, 2019.
- [112] S. S. Magendran *et al.*, "Synthesis of organic phase change materials (PCM) for energy storage applications: A review," *Journal of Energy Storage*, vol. 20, p. 100399, 2019.
- [113] P. K. S. Rathore, S. K. Shukla, and B. Materials, "Potential of macroencapsulated PCM for thermal energy storage in buildings: A comprehensive review," *Construction and Building Materials*, vol. 225, pp. 723–744, 2019.
- [114] L. Tan, A. Date, G. Fernandes, B. Singh, and S. Ganguly, "Efficiency gains of photovoltaic system using latent heat thermal energy storage," *Energy Procedia*, vol. 110, pp. 83–88, 2017.
- [115] E. Günther, S. Hiebler, H. Mehling, and R. Redlich, "Enthalpy of phase change materials as a function of temperature: Required accuracy and suitable measurement methods," *International Journal of Thermophysics*, vol. 30, no. 4, pp. 1257–1269, 2009.
- [116] Lilley, A. K. Menon, S. Kaur, S. Lubner, and R. S. Prasher, "Phase change materials for thermal energy storage: A perspective on linking phonon physics to performance," *Journal of Applied Physics*, vol. 130, no. 22, 2021.
- [117] W. Wei *et al.*, "A continuous 24-hour power generated PV-TEG-PCM hybrid system enabled by solar diurnal photovoltaic/thermal conversion and nocturnal sky radiative cooling," *Applied Energy*, vol. 321, p. 119086, 2024.
- [118] Al Maaari and H. M. Ali, "Technical method in passive cooling for photovoltaic panels using phase change material," *Case Studies in Thermal Engineering*, vol. 49, p. 103283, 2023.
- [119] H. M. Maghrabie, A. Mohamed, A. M. Fahmy, and A. A. A. Samee, "Performance enhancement of PV panels using phase change material (PCM): An experimental implementation," *Case Studies in Thermal Engineering*, vol. 42, p. 102741, 2023.