Journal of Engineering, Technology & Applied Science
p-ISSN: 2721-7949, e-ISSN: 2721-8090

Original Research Paper

Factors Influencing the Efficiency of Solar Energy Systems

Val Hyginus Udoka Eze[1*], Kiiza Richard[1], Kelechi John Ukagwu[1], Wisdom Okafor[2]

[1] *Department of Electrical, Faculty of Telecommunication and Computer Engineering, Kampala International University. Uganda.*
[2] *Department of Computer Science and Technology, University of Bedfordshire. Luton, United Kingdom.*

Article History
Received:
27.08.2024

Revised:
15.09.2024

Accepted:
24.09.2024

***Corresponding Author:**
Val Hyginus Udoka Eze
Email:
udoka.eze@kiu.ac.ug

Abstract: The efficiency of solar panels is significantly influenced by temperature and irradiance, which are crucial in solar energy conversion. As temperatures rise, solar panel efficiency typically decreases due to increased electrical resistance, resulting in lower output voltage and power production. This efficiency loss is quantified by the temperature coefficient, indicating the drop per degree Celsius above 25°C. Advanced cooling systems and optimal thermal management can mitigate these effects. Irradiance, the sunlight intensity reaching the panels, directly affects electricity generation. While higher irradiance increases efficiency by providing more photons for conversion, it can also raise temperatures, negatively impacting performance. Solar panels achieve maximum efficiency under optimal irradiance and moderate temperatures, typically 1000 W/m² at 25°C. Variations in irradiance due to geographical location, time of day, and weather conditions cause fluctuations in power output. Efficient system design must consider local irradiance patterns and utilize tracking systems to maintain optimal panel orientation. To optimize efficiency, innovative methods such as advanced materials, cooling techniques, and smart tracking systems are employed. Additionally, integrating energy storage solutions and predictive analytics helps manage environmental impacts. Proper design, installation, and maintenance strategies are crucial for maximizing solar panel efficiency and lifespan under varying conditions. Understanding the interplay between temperature and irradiance is essential for advancing solar energy technologies, and enhancing their reliability and effectiveness in diverse environments.

Keywords: Maximum Powerpoint Tracking Techniques, Solar Efficiency, Solar Energy System, Solar Irradiance, Temperature.

1. Introduction

Solar energy has emerged as a promising alternative to conventional energy sources due to its abundant availability and environmentally friendly attributes [1]. However, the efficiency of solar energy systems remains a critical concern, influencing their widespread adoption and practical viability. Understanding the multifaceted factors that impact the efficiency of solar energy systems is crucial for optimizing their performance and enhancing their contribution to the global energy mix. Technological advancements play a crucial role in improving the efficiency of solar energy systems [2]. Innovations in photovoltaic (PV) cell design, such as the development of thin-film, multi-junction, and perovskite solar cells, have led to significant enhancements in conversion efficiency [3]. Additionally, improvements in solar tracking mechanisms, energy storage technologies, and system integration have contributed to maximizing energy yield and overall system efficiency [4] [5]. Beyond technological considerations, environmental factors exert a profound influence on the efficiency of solar energy systems. Variations in solar irradiance, atmospheric conditions, and geographical location significantly impact the energy output of solar panels. Moreover, factors like dust accumulation, shading, and temperature fluctuations can degrade system performance over time, necessitating effective maintenance and mitigation strategies [6]. Furthermore, socioeconomic and optimization-related aspects shape the efficiency and deployment of solar energy systems.

One of the critical parameters that affect the minimum solar cell efficiency at which the solar cell operates is the ambient temperature. Solar cells convert photon fluxes into electrical energy [7]. The temperature dependence is attributed to the phonon-excited carriers in the non-ideal materials or imperfections in the solar cell's lattice structure that cause the recombination of the excited carriers. Electrons and holes generated under the influence of absorption of higher energetic photons could also scatter with the lattice imperfections and generate excess carriers in the solar cell's material, leading to thermalization of the scattering [8]. An illuminated single-material, photovoltaic cell is essentially an equalizer of the material's charge carriers drift and diffusion, of which both are inversely proportional to the lattice temperature. Hence, it is necessary to consider that knowledge of how the solar efficiency of the photovoltaic cells would be modulated as a function of various parameters must be considered for its practical usefulness and adaptability.

The essence of solar power generation is the conversion of electromagnetic radiation from the sun into electricity using this solar photovoltaic technology [9]. A limitation to problems of dependence on fossil fuels and the ethical considerations associated with the various available renewable energy technologies being harnessed as an alternative energy source is that the suitable return on investment for various sustainable energy technologies could only be realized on long durations, out of which is the environmental benefits. Full utilization of solar power has been hindered by a drawback in the solar efficiency stacks that have maintained state-of-the-art efficiencies of the 1st, 2nd, and 3rd generation photovoltaics about 16.5%, 33.3%, and 42.8% respectively [10]. The successful practical harnesses of solar power generation rely on various theoretical and practical considerations as highlighted below in the subsections of this research paper.

2. Literature Review

2.1. Factors Affecting Solar Photovoltaic Efficiency

Factors affecting solar photovoltaic efficiency, are:

1) Temperature

Temperature plays a critical role in the efficiency of solar panels. Although solar panels are designed to convert sunlight into electricity, their performance can be affected by temperature fluctuations [11]. Solar panels have a temperature coefficient that indicates how their efficiency decreases as the temperature rises. Most solar panels experience a decline in efficiency as the temperature increases because the materials used in solar panels are sensitive to temperature changes [11]. Typically, for every degree Celsius increase in temperature above the standard testing conditions (25°C), solar panel efficiency decreases by a certain percentage. Solar panels operate more efficiently when they are cooler [13]. However, solar panels not only absorb sunlight but also absorb heat from their surroundings. This heat can lead to a decrease in efficiency due to increased resistance in the electrical circuits.

The operating temperature of solar panels varies depending on factors such as geographical location, time of day, and weather conditions. In hot climates or during peak sunlight hours, solar panels can significantly heat up, leading to reduced efficiency. Some advanced solar installations incorporate cooling systems to counteract the effects of high temperatures. These systems can range from simple passive cooling techniques like airflow design to more complex active cooling methods like water circulation or the use of coolants. High temperatures can accelerate the degradation of solar panel components over time, resulting in a decrease in the overall lifespan and efficiency of the solar panel system [14] [15]. Proper thermal management is crucial for maintaining the efficiency and longevity of solar panels. This includes factors such as panel orientation, spacing, and the use of shading devices to minimize heat buildup. Therefore, while solar panels can still generate electricity in high-temperature environments, their efficiency may be reduced compared to cooler conditions. Proper design, installation, and maintenance are essential for optimizing solar panel performance in varying temperature conditions.

2) Irradiance

Irradiance is a vital factor in determining the efficiency of solar panels as it represents the amount of sunlight that reaches the surface of the panels per unit area [16]. Solar panels function by converting sunlight into electricity through the photovoltaic effect, where photons from sunlight dislodge electrons from atoms, thus creating an electric current [17] [18]. Consequently, the intensity of sunlight directly impacts the electricity output.

Influences of irradiance on solar photovoltaic efficiency, are:

1) Direct Relationship
   Solar panels generate more electricity when they receive higher levels of irradiance. More sunlight means more photons interacting with the photovoltaic cells, leading to a greater generation of electricity [19].
2) Peak Performance
   Solar panels are typically tested and rated under standard Test conditions (STC) for irradiance and temperature to be 1000Wm2 and 25°C respectively. Under these ideal conditions, solar panels achieve their maximum efficiency. However, in real-world scenarios, irradiance levels can vary throughout the day and across different seasons, affecting the actual output of solar panels [20].
3) Variation in Output
   As irradiance levels change, the output of solar panels also fluctuates. For example, on cloudy days or during early morning or late afternoon hours, irradiance levels are lower, resulting in reduced electricity generation [21]. Conversely, solar panels produce more electricity during peak sunlight hours, such as midday on a clear day.
4) Geographical Factors
   Irradiance levels vary based on geographical location, time of year, weather patterns, and other factors [22]. Regions closer to the equator generally receive higher levels of irradiance throughout the year compared to areas farther away. Understanding the local irradiance patterns is important for accurately estimating the energy production of solar systems.
5) Angle of Incidence
   The angle at which sunlight strikes the solar panels also affects irradiance and consequently, solar efficiency. Solar panels are most efficient when sunlight hits them perpendicularly [23]. As the angle of incidence increases, the effective irradiance decreases, reducing the output of the solar panels.

2.2. Effect of Temperature on Solar Photovoltaic Efficiency

2.2.1. Effects of High Temperature on Solar Photovoltaic Efficiency

The Effects of High Temperature on Solar Efficiency are crucial for understanding the performance of solar energy systems [24] [25]. High Temperature affects solar efficiency through the following:

1) Temperature coefficient
   This is the measure of the degree to which the efficiency of solar panels decreases with each degree Celsius increase in temperature [26]. Solar panels are most efficient at cooler temperatures, but as the temperature rises, their efficiency decreases.
2) Impact on output
   Higher temperatures can reduce the output voltage of solar panels, which in turn affects their ability to generate electricity efficiently [27]. This reduction in output voltage ultimately leads to a decrease in overall power production.

3) Heat dissipation
   Solar panels absorb sunlight to convert it into electricity, but they also absorb heat energy [28]. When the panels get too hot, they become less efficient at converting sunlight into electricity. Therefore, effective heat dissipation mechanisms are crucial to maintain optimal efficiency. Some advanced solar installations incorporate cooling systems to mitigate the effects of high temperatures on solar panel efficiency. These cooling systems can utilize passive cooling methods, such as airflow design, or active cooling methods like water circulation systems to solve the problems of heating.
4) Geographical location and climate
   The temperature coefficient and its effect on solar efficiency can vary depending on the geographical location [29]. Areas with higher average temperatures may experience more significant decreases in efficiency during hot weather compared to cooler regions.

2.2.2. Effects of Low Temperature on Solar Photovoltaic Efficiency

The Effects of low Temperature on Solar Efficiency are crucial for understanding the performance of solar energy systems [30] [31]. Low Temperature affects solar efficiency through the following:

1) Reduced output
   As the temperature drops, the semiconductor materials used in solar cells conduct electricity less efficiently, resulting in a decrease in power output [32]. In addition, lower temperatures can increase the internal resistance of solar panels, which in turn reduces the flow of electricity and decreases overall efficiency.
2) Thermal coefficient
   Solar panels also have a thermal coefficient, which indicates how their efficiency decreases with increasing temperature [33]. Different types of solar panels have different thermal coefficients, but generally, a decrease in temperature leads to an increase in efficiency.
3) Tilt Angle
   In areas where snowfall is common, snow accumulation on solar panels can block sunlight and significantly reduce efficiency until the snow is cleared [34]. This is why it is important to adjust the tilt angle of solar panels to maximize sunlight exposure and reduce the impact of snow accumulation in areas prone to snowfall.
4) Battery performance
   Low temperatures can also affect battery performance in off-grid solar systems that utilize batteries for energy storage [35] [36]. Cold temperatures can reduce battery capacity and slow down chemical reactions, leading to decreased overall system efficiency. To combat this, battery heating systems can be used to maintain battery performance in cold temperatures.

Strategies to Curtail the Effect of Low Temperatures on Solar Photovoltaic Efficiency

1) Adjusting the tilt angle of solar panels can help maximize sunlight exposure and reduce the impact of snow accumulation.
2) Providing adequate insulation beneath and around solar panels can help retain heat, mitigating some of the efficiency losses associated with low temperatures.
3) Some advanced solar installations also incorporate heating systems to prevent snow accumulation and maintain optimal operating temperatures for the panels.

2.3. Effect of Irradiance on Solar Photovoltaic Efficiency

The relationship between irradiance and solar efficiency is crucial for understanding how effectively a solar photovoltaic (PV) system converts sunlight into electricity [37]. Irradiance refers to the power per unit area (typically measured in watts per square meter, W/m²) of sunlight that reaches the Earth's surface [38]. It depends on various factors, such as the time of day, season, weather conditions, and geographical location. Higher irradiance means more sunlight is available for conversion into electricity by solar panels. Solar efficiency measures the effectiveness of a solar PV system in converting sunlight into electricity [39]. It is typically represented as a percentage and varies depending on the type of solar panel technology in use.

2.3.1. Relationship between Irradiance and Solar Photovoltaic Efficiency

The relationship between irradiance and solar photovoltaic efficiency, are:

1) Direct Proportionality
   Generally, higher irradiance levels lead to higher electricity production from solar panels, assuming all other factors remain constant [40]. This is because higher irradiance provides more photons for conversion, resulting in increased electrical output.
2) Non-linear Relationship
   While higher irradiance generally leads to higher electricity production, the relationship between irradiance and solar efficiency is not always linear [41]. Solar panels have a maximum power point (MPP) at which they operate most efficiently. At very low irradiance levels, the efficiency may drop significantly, and at very high irradiance levels, the efficiency may plateau or even decrease due to factors such as temperature effects and shading.
3) Temperature Effects
   Higher irradiance levels can also lead to increased temperatures in solar panels, which can negatively affect efficiency [42]. Most solar panels experience a decrease in efficiency as temperatures rise above a certain threshold.

2.3.2. Effects of High Irradiance on Solar Photovoltaic Efficiency

Effects of High Irradiance on Solar Photovoltaic Efficiency, are:

1) Solar panels generally produce more electricity when they receive higher irradiance levels. This is because sunlight contains photons with more energy, which can generate a higher voltage and current in the solar cells.
2) Operating temperature is crucial in solar panel efficiency at high irradiance levels. As solar panels absorb sunlight, they also absorb heat [43]. High temperatures can decrease the efficiency of solar panels. Most solar cells perform less effectively as temperature rises due to increased electron-hole recombination rates and changes in the semiconductor material properties.
3) The impact of high irradiance levels on solar cell efficiency varies depending on the type of solar cell. For instance, crystalline silicon solar cells typically experience a reduction in efficiency at high irradiance levels due to increased temperature [44]. On the other hand, thin-film solar cells may have a more stable performance. Furthermore, excessive irradiance levels can potentially damage solar cells when not designed to handle high levels of sunlight. This can lead to the degradation of the solar cells over time, reducing their efficiency and lifespan.

Solar tracking systems effectively manage high irradiance levels by continuously adjusting the orientation of solar panels to maximize sunlight exposure throughout the day. By optimizing the angle of incidence between the sunlight and the panels, these tracking systems significantly enhance overall efficiency

2.3.3. Effects of Low Irradiance on Solar Photovoltaic Efficiency

Low irradiance, which refers to low levels of sunlight intensity, can have several effects on the efficiency of solar panels [45]. These effects include reduced power output, decreased efficiency, voltage drop, temperature sensitivity, impact on tracking systems, battery performance, and system design considerations.

1) When irradiance levels are low, there is less sunlight available to generate electricity, leading to a reduction in the power output of the solar panels. Additionally, solar panel efficiency typically decreases as irradiance levels decrease. This is because solar cells operate most efficiently when they receive optimal levels of sunlight. At lower irradiance levels, the conversion efficiency of solar cells tends to decrease, resulting in lower overall system efficiency.
2) In low light conditions, the voltage output of solar panels tends to drop. This can affect the performance of devices powered by solar energy, as they may not receive sufficient voltage to operate efficiently or at all. Furthermore, low irradiance conditions often coincide with lower temperatures, especially during early mornings, late evenings, or cloudy days. Solar panels typically operate more efficiently at lower temperatures. However, excessively low temperatures can lead to decreased performance due to increased resistance in the electrical circuits.
3) Some solar installations use tracking systems to optimize the angle of the solar panels relative to the sun [46]. In low irradiance conditions, these tracking systems may not operate

optimally, reducing the efficiency gains they would otherwise provide. Moreover, low irradiance conditions can impact the performance and lifespan of batteries used in solar systems with energy storage capabilities. If these batteries are not properly sized or maintained, their performance can be affected.

To mitigate the effects of low irradiance on solar efficiency, system designers may incorporate strategies such as oversized panels, energy storage systems, and alternative power sources. Oversized panels increase the surface area available for capturing sunlight, enhancing energy generation even under suboptimal conditions. Energy storage systems, such as batteries, store excess energy produced during peak sunlight hours for use during periods of low irradiance. Additionally, integrating alternative power sources, such as wind or hydro, can supplement solar power and ensure a more reliable energy supply.

Finally, solar panels can generate electricity under low irradiance conditions, their efficiency and power output are significantly reduced compared to optimal conditions. Proper system design, including the selection of appropriate components and configurations, can effectively mitigate the impact of low irradiance on solar energy systems, ensuring consistent and reliable energy generation.

2.4. Combined Effects of Temperature and Irradiance on Solar Photovoltaic

Interactions between temperature and irradiance are crucial in various fields, especially in areas like environmental science, climate studies, and renewable energy.

Interactions between temperature and irradiance on solar photovoltaic, are:

1) Solar Energy Production
   In solar panels, temperature and irradiance affect the efficiency of energy conversion. While high irradiance (sunlight intensity) increases the energy output, high temperatures decrease efficiency. This is because as the temperature rises, the semiconductor materials in solar panels become less efficient at converting sunlight into electricity [47]. Thus, the optimal operating conditions for solar panels involve balancing irradiance and temperature.
2) Climate and Weather Patterns
   Temperature and irradiance are both key components of Earth's climate system. Temperature changes affect atmospheric circulation patterns, which in turn influence the distribution of irradiance across the globe [48]. Likewise, variations in irradiance impact surface temperatures, contributing to regional climate variations and weather patterns.
3) Greenhouse Gas Emissions
   Interactions between temperature and irradiance are central to understanding the mechanisms driving greenhouse gas emissions and climate change. Increases in temperature can lead to the release of greenhouse gases from sources like permafrost, amplifying global warming. Similarly, changes in irradiance can affect the Earth's energy balance, influencing temperature patterns and feedback mechanisms.
4) Urban Heat Island Effect
   In urban areas, interactions between temperature and irradiance contribute to the urban heat island effect. High levels of irradiance absorbed by buildings and pavement increase surface temperatures, leading to localized warming. This phenomenon exacerbates heat-related issues in cities, impacting human health, energy consumption, and urban ecosystems.

These interactions between temperature and irradiance are essential for predicting the impacts of climate change, optimizing renewable energy systems, and implementing effective mitigation strategies. It requires interdisciplinary approaches that integrate knowledge from fields such as meteorology, climatology, ecology, and materials science.

For solar panels, the optimal temperature and irradiance conditions for maximum efficiency typically involve moderate temperatures and high irradiance levels. Solar panels work most efficiently when they are within the optimum temperature range. As temperature increases, the efficiency of solar panels tends to decrease [49] [50]. This is because higher temperatures can lead to increased resistance in the solar cells and can also reduce the voltage output. However, extremely low temperatures can also affect efficiency, so a moderate temperature range is ideal. Generally, solar panels operate optimally at standard test condition (STC) temperatures value of 25°C (77°F). Higher irradiance levels mean more photons are striking the solar cells, which increases the potential for electricity generation. Therefore, maximum efficiency is typically achieved when solar panels receive high levels of irradiance, such as on clear, sunny days with direct sunlight. Hence, for a solar panel to perform effectively, a moderate temperature of 25°C (77°F) and high irradiance levels from direct sunlight of 1000Wm2 are required.

3. Methodology

This study uses both laboratory experiments and field studies to assess how efficient solar panels are in different temperature and irradiance scenarios. During the experimental stage, specific conditions will be controlled in order to separate the impact of temperature and irradiance on the performance of the panel. A solar simulator will mimic irradiance levels ranging from 200 W/m² to 1200 W/m², while temperature control systems like Peltier coolers will regulate panel surface temperatures from 10°C to 60°C. Voltage, current, and power output will be monitored to determine the temperature coefficient and evaluate efficiency losses. Sophisticated tools such as pyranometers and thermocouples will guarantee accurate tracking of irradiance and temperature, enabling a thorough examination of how these factors affect the efficiency of solar panels.

Field research will enhance laboratory discoveries by studying the performance of solar panels in actual environments. Solar panels will be placed at various locations with diverse geographical and climatic features to collect differences in sunlight exposure, temperatures, and weather. Data loggers will track performance metrics in real-time, such as power output and efficiency changes, throughout different times of day and seasons. These observations will help confirm lab findings and investigate strategies, like cooling systems and tracking devices, for maximizing panel performance. The research aims to offer practical insights for enhancing the design, installation, and operation of solar panels in various environments by combining results from controlled experiments and field studies.

4. Finding and Discussion

Methods to improve solar efficiency under varying temperatures and irradiance, are:

4.1. Tracking Systems

Maximizing the energy output of solar panels regardless of external conditions requires the use of various techniques. Research and development into advanced photovoltaic materials can enhance efficiency. Perovskite solar cells have shown promise due to their high efficiency and tolerance to temperature variations. Another technique is the use of bifacial solar panels, which can capture sunlight from both the front and back sides, increasing energy generation, especially in environments with reflective surfaces like snow or sand. To ensure maximum power output under changing environmental conditions, maximum power point tracking (MPPT) algorithms continuously adjust the electrical operating point of the solar panels [51] [52] [53]. This optimization helps mitigate the impact of temperature and irradiance fluctuations. Additionally, implementing thermal management systems such as liquid cooling or air cooling can help maintain optimal operating temperatures, especially in hot climates, as heat can reduce solar panel efficiency.

Adjustment of the tilt angle and orientation of solar panels dynamically based on real-time weather conditions and sun position are also paramount as the energy captured throughout the day can be maximized and be used as a compensator for changes in irradiance [54]. Integrating energy storage solutions like batteries allows excess energy generated during optimal conditions to be stored and used during periods of low irradiance or high demand, ensuring a more consistent energy supply.

Predictive Analytics and weather forecasting serve as pivotal instruments in optimizing energy generation. By using weather forecasting data and predictive analytics, changes in temperature and irradiance can be anticipated, enabling proactive adjustments in system parameters. Implementing anti-soiling coatings and automated cleaning mechanisms can help maintain optimal performance by preventing the accumulation of dust, dirt, and debris on solar panels, especially in arid regions.

Analyzing and mitigating shading effects caused by nearby structures, vegetation, or temporary obstructions like clouds is also crucial [55]. This prevents significant drops in energy output due to partial shading. Designing solar installations in a modular and scalable manner allows for easier expansion and reconfiguration to adapt to changing environmental conditions and energy demands. By implementing these methods and continuously innovating in the field of solar technology, it is possible to improve the efficiency and reliability of solar energy systems under varying temperature and irradiance conditions.

4.2. Cooling Techniques

Improving solar efficiency under varying temperatures and irradiance involves implementing strategies to mitigate the negative impacts of these factors on solar panel performance. Some of the techniques and methods to be adopted to enhance solar efficiency are as follows:

1) Active Cooling Systems
   Implementing active cooling systems such as water cooling or air cooling can help regulate the temperature of solar panels, preventing overheating and maintaining optimal operating conditions [56] [57]. These systems involve circulating water or air through the panels to dissipate heat.
2) Passive Cooling Techniques
   Utilizing passive cooling techniques like designing panels with heat-dissipating materials or incorporating thermal insulation can help naturally lower the temperature of solar panels without the need for additional energy input [58].
3) Selective Solar Absorbers
   Using selective coatings on solar panels can enhance their ability to absorb sunlight while minimizing heat absorption [59]. These coatings selectively transmit or reflect certain wavelengths of light, reducing the amount of energy converted into heat.
4) Tilt and Orientation Optimization
   Adjusting the tilt and orientation of solar panels based on the angle of the sun throughout the day can optimize energy capture while reducing the impact of temperature variations [54] [60]. This can be achieved through tracking systems or optimizing the fixed tilt angle.
5) Bifacial Solar Panels
   Bifacial solar panels can capture sunlight from both the front and rear sides, increasing energy generation and reducing temperature buildup compared to traditional single-sided panels [61]. This design allows for more efficient use of available irradiance.
6) Encapsulation Materials
   Using advanced encapsulation materials with high thermal conductivity can help dissipate heat more effectively, preventing temperature-induced degradation and improving long-term performance [62].
7) Smart Inverter Technology
   Smart inverters with built-in temperature and irradiance sensors can dynamically adjust the power output of solar panels to optimize efficiency under varying environmental conditions [63]. They can also incorporate algorithms to maximize energy yield based on real-time data.
8) Shading and Ventilation
   Installing shading devices or providing adequate ventilation around solar panels can help reduce temperature buildup caused by direct sunlight exposure, especially in hot climates [64]
9) Cleaning and Maintenance
   Regular cleaning and maintenance of solar panels are essential for optimal performance. Removing dust, dirt, and other debris from the surface can prevent shading and improve light absorption, thereby mitigating temperature-related efficiency losses [65]
10) Advanced Materials and Manufacturing Techniques
   Continued research into advanced materials and manufacturing techniques can lead to the development of solar panels with enhanced thermal stability and improved efficiency under varying environmental conditions [66].

4.3. Concentrated Solar Power

Improving the efficiency of Concentrated Solar Power (CSP) systems under varying temperature and irradiance conditions is crucial for maximizing energy output and ensuring the viability of CSP technology [67].

Methods of enhancing the efficiency of CSP systems

1) Advanced Heat Transfer Fluids
   Using high-performance heat transfer fluids with excellent thermal stability and heat capacity can enhance the efficiency of CSP systems. These fluids should maintain their properties over a wide temperature range to ensure efficient heat transfer from the solar receiver to the power cycle.

2) Thermal Energy Storage (TES)
   Integrating thermal energy storage systems allows CSP plants to store excess heat generated during periods of high solar irradiance and use it later during cloudy periods or at night. Advanced TES technologies, such as molten salt or phase change materials, can improve system efficiency by providing dispatchable power and extending operating hours.
3) Optimized Receiver Design
   Developing innovative receiver designs that can withstand high temperatures and efficiently absorb solar radiation is essential. Selective coatings and materials with high thermal conductivity can enhance receiver performance under varying irradiance conditions.
4) Optical Enhancements
   Employing advanced optical components, such as high-performance mirrors or lenses, can improve the concentration of solar energy onto the receiver, thereby increasing system efficiency. Additionally, incorporating tracking systems that adjust the position of mirrors or lenses to optimize solar capture throughout the day enhances overall performance.
5) Integrated Hybrid Systems
   Combining CSP with other renewable energy technologies like photovoltaics (PV) or wind power can create hybrid systems that utilize complementary energy sources to mitigate the effects of fluctuating solar irradiance. Hybridization can improve overall system reliability and energy output.
6) Predictive Analytics and Control Systems: Implementing predictive analytics algorithms and advanced control systems can optimize the operation of CSP plants by forecasting solar irradiance and adjusting system parameters in real time to maximize efficiency. Machine learning techniques can be employed to improve predictive accuracy and control strategies.
7) Site Selection and Plant Layout Optimization: Choosing optimal locations for CSP plants based on solar resource availability and environmental factors can significantly impact system performance. Additionally, optimizing the layout of solar fields and minimizing shading effects can enhance energy capture efficiency.
8) Maintenance and Cleaning Strategies: Regular maintenance and cleaning of solar collectors and optical components are essential to prevent efficiency losses due to dust, dirt, or degradation of reflective surfaces. Implementing automated cleaning systems and proactive maintenance schedules can help maintain optimal performance.

By implementing these methods, CSP systems can achieve higher efficiencies and improve their reliability under varying temperature and irradiance conditions, thereby contributing to the growth of renewable energy generation.

4.3. Solar Efficiency in Different Climates

Solar efficiency in different climates, are:

1) Sunny Climate
   Regions with high sun exposure, such as deserts or tropical areas, generally have the highest solar efficiency [68]. The abundance of sunlight ensures that solar panels receive maximum irradiance, resulting in optimal energy production.
2) Moderate Climates
   Areas with moderate sunlight, like temperate regions, also offer good solar efficiency. While they may not receive as much sunlight as sunny climates, they still have sufficient irradiance for effective solar power generation.
3) Cloudy or Overcast Climates
   Regions with frequent cloud cover or overcast skies may experience reduced solar efficiency. Clouds can block sunlight and diffuse irradiance, lowering the amount of energy that solar panels can convert. However, solar power generation is still feasible in cloudy climates, albeit with lower efficiency compared to sunny regions.
4) Cold Climates
   Solar panels operate more efficiently at cooler temperatures, which can offset the reduction in sunlight intensity experienced during colder seasons. However, snow accumulation on panels can temporarily reduce efficiency until it melts or is cleared.

5) Extreme Climates

Extreme climates, such as very hot or very cold regions, may pose challenges to solar panel efficiency depending on the stability and Optimization Bandgap of the Perovskite Materials in use [69]. High temperatures can cause some degradation in panel performance over time, although modern panels are designed to withstand such conditions. Similarly, extreme cold can affect efficiency, but it's often less of a concern compared to other factors like sunlight availability and snow accumulation.

5. Conclusion

The efficiency of solar energy systems is influenced by an intricate combination of technological and environmental factors. Technological advancements, such as the creation of high-efficiency solar cells and improved system designs, are crucial for enhancing the performance of both photovoltaic and solar thermal systems. Environmental factors, such as solar irradiance, temperature, shading, and dust, also have a significant impact on solar panel performance. In addition, system-level considerations like tilt angle, orientation, and tracking mechanisms play a vital role in maximizing efficiency. To optimize solar energy systems and encourage their use as a sustainable energy source, it is essential to have a thorough understanding of these factors and how they interact with each other.

References

[1] A. Hussain, S. M. Arif, and M. Aslam, “Emerging renewable and sustainable energy technologies: State of the art,” *Renewable and Sustainable Energy Reviews*, vol. 71, pp. 12–28, 2017.
[2] S. S. M. Ajarostaghi and S. S. Mousavi, “Solar energy conversion technologies: Principles and advancements,” in *Solar Energy Advancements in Agriculture and Food Production Systems*, pp. 29–76, 2022.
[3] M. Yamaguchi, F. Dimroth, J. F. Geisz, and N. J. Ekins-Daukes, “Multi-junction solar cells paving the way for super-high efficiency,” *Journal of Applied Physics*, vol. 129, no. 24, 2021.
[4] V. H. U. Eze, O. Robert, N. I. Sarah, J. S. Tamball, O. F. Uzoma, and W. O. Okafor, “Transformative potential of thermal storage applications in advancing energy efficiency and sustainability,” *IDOSR Journal of Applied Sciences*, vol. 9, no. 1, pp. 51–64, 2024.
[5] V. H. U. Eze, J. S. Tamball, O. F. Uzoma, I. Sarah, O. Robert, and W. O. Okafor, “Advancements in energy efficiency technologies for thermal systems: A comprehensive review,” *INOSR Applied Sciences*, vol. 12, no. 1, pp. 1–20, 2024.
[6] K. Hasan, S. B. Yousuf, M. S. H. K. Tushar, B. K. Das, P. Das, and M. S. Islam, “Effects of different environmental and operational factors on the PV performance: A comprehensive review,” *Energy Science & Engineering*, vol. 10, no. 2, pp. 656–675, 2022.
[7] V. B. Omubo-Pepple, C. Israel-Cookey, and G. I. Alaminokuma, “Effects of temperature, solar flux and relative humidity on the efficient conversion of solar energy to electricity,” *European Journal of Scientific Research*, vol. 35, no. 2, pp. 173–180, 2009.
[8] J. M. Richter et al., “Ultrafast carrier thermalization in lead iodide perovskite probed with two-dimensional electronic spectroscopy,” *Nature Communications*, vol. 8, no. 1, pp. 376, 2017.
[9] N. Keskar Vinaya, “Electricity generation using solar power,” *International Journal of Engineering Research & Technology (IJERT)*, vol. 2, no. 2, pp. 1–5, 2013.
[10] S. Bellani et al., “Solution-processed two-dimensional materials for next-generation photovoltaics,” *Chemical Society Reviews*, vol. 50, no. 21, pp. 11870–11965, 2021.
[11] C. Sun, Y. Zou, C. Qin, B. Zhang, and X. Wu, "Temperature effect of photovoltaic cells: A review," *Advanced Composites and Hybrid Materials*, vol. 5, no. 4, pp. 2675-2699, 2022.
[12] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world–a review," *Energy Procedia*, vol. 33, pp. 311-321, 2013.
[13] A. R. Amelia, Y. M. Irwan, W. Z. Leow, M. Irwanto, I. Safwati, and M. Zhafarina, "Investigation of the effect temperature on photovoltaic (PV) panel output performance," *International Journal of Advanced Science Engineering Information Technology*, vol. 6, no. 5, pp. 682-688, 2016.

[14] M. Aghaei, A. Fairbrother, A. Gok, S. Ahmad, S. Kazim, K. Lobato, ... and J. Kettle, "Review of degradation and failure phenomena in photovoltaic modules," *Renewable and Sustainable Energy Reviews*, vol. 159, pp. 112160, 2022.

[15] V. Sharma and S. S. Chandel, "Performance and degradation analysis for long term reliability of solar photovoltaic systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 753-767, 2013.

[16] M. S. Salim, J. M. Najim, and S. M. Salih, "Practical evaluation of solar irradiance effect on PV performance," *Energy Science and Technology*, vol. 6, no. 2, pp. 36-40, 2013.

[17] A. Parretta, A. Sarno, and L. R. Vicari, "Effects of solar irradiation conditions on the outdoor performance of photovoltaic modules," *Optics Communications*, vol. 153, no. 1-3, pp. 153-163, 1998.

[18] A. Al-Bashir, M. Al-Dweri, A. AlGhandoor, B. Hammad, and W. AlKouz, "Analysis of effects of solar irradiance, cell temperature and wind speed on photovoltaic systems performance," *International Journal of Energy Economics and Policy*, vol. 10, no. 1, pp. 353-359, 2020.

[19] T. M. Razykov, C. S. Ferekides, D. Morel, E. Stefanakos, H. S. Ullal, and H. M. Upadhyaya, "Solar photovoltaic electricity: Current status and future prospects," *Solar Energy*, vol. 85, no. 8, pp. 1580-1608, 2011.

[20] D. Leitão, J. P. N. Torres, and J. F. Fernandes, "Spectral irradiance influence on solar cells efficiency," *Energies*, vol. 13, no. 19, pp. 5017, 2020.

[21] M. Alshawaf, R. Poudineh, and N. S. Alhajeri, "Solar PV in Kuwait: The effect of ambient temperature and sandstorms on output variability and uncertainty," *Renewable and Sustainable Energy Reviews*, vol. 134, pp. 110346, 2020.

[22] T. Huld, and A. M. Gracia Amillo, "Estimating PV module performance over large geographical regions: The role of irradiance, air temperature, wind speed and solar spectrum," *Energies*, vol. 8, no. 6, pp. 5159-5181, 2015.

[23] J. Coston, C. Robinson, B. King, J. Braid, D. Riley, and J. S. Stein, "Effects of Solar Angle of Incidence on Intramodular Photovoltaic Irradiance Uniformity," in *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, pp. 1499-1503, 2021.

[24] D. Meneses-Rodríguez, P. P. Horley, J. Gonzalez-Hernandez, Y. V. Vorobiev, and P. N. Gorley, "Photovoltaic solar cells performance at elevated temperatures," *Solar Energy*, vol. 78, no. 2, pp. 243-250, 2005.

[25] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world–a review," *Energy Procedia*, vol. 33, pp. 311-321, 2013.

[26] B. R. Paudyal, and A. G. Imenes, "Investigation of temperature coefficients of PV modules through field measured data," *Solar Energy*, vol. 224, pp. 425-439, 2021.

[27] K. Hasan, S. B. Yousuf, M. S. H. K. Tushar, B. K. Das, P. Das, and M. S. Islam, "Effects of different environmental and operational factors on the PV performance: A comprehensive review," *Energy Science & Engineering*, vol. 10, no. 2, pp. 656-675, 2022.

[28] M. Rajvikram, and G. Sivasankar, "Experimental study conducted for the identification of best heat absorption and dissipation methodology in solar photovoltaic panel," *Solar Energy*, vol. 193, pp. 283-292, 2019.

[29] H. K. Firozjaei, M. K. Firozjaei, O. Nematollahi, M. Kiavarz, and S. K. Alavipanah, "On the effect of geographical, topographic and climatic conditions on feed-in tariff optimization for solar photovoltaic electricity generation: A case study in Iran," *Renewable Energy*, vol. 153, pp. 430-439, 2020.

[30] M. Jahanpanah, S. J. Sadatinejad, A. Kasaeian, M. H. Jahangir, and H. Sarrafha, "Experimental investigation of the effects of low-temperature phase change material on single-slope solar still," *Desalination*, vol. 499, pp. 114799, 2021.

[31] N. S. Ganesh, and T. Srinivas, "Design and modeling of low temperature solar thermal power station," *Applied Energy*, vol. 91, no. 1, pp. 180-186, 2012.

[32] P. K. Dash, and N. C. Gupta, "Effect of temperature on power output from different commercially available photovoltaic modules," *International Journal of Engineering Research and Applications*, vol. 5, no. 1, pp. v148-151, 2015.

[33] M. Rajvikram, S. Leoponraj, S. Ramkumar, H. Akshaya, and A. Dheeraj, "Experimental investigation on the abasement of operating temperature in solar photovoltaic panel using PCM and aluminium," *Solar Energy*, vol. 188, pp. 327-338, 2019.

[34] R. E. Pawluk, Y. Chen, and Y. She, "Photovoltaic electricity generation loss due to snow–A literature review on influence factors, estimation, and mitigation," *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 171-182, 2019.

[35] V. H. U. Eze, J. S. Tamball, O. Robert, and W. O. Okafor, "Advanced Modeling Approaches for Latent Heat Thermal Energy Storage Systems," *IAA Journal of Applied Sciences*, vol. 11, no. 1, pp. 49-56, 2024.

[36] V. Svoboda, H. Wenzl, R. Kaiser, A. Jossen, I. Baring-Gould, J. Manwell, and D. U. Sauer, "Operating conditions of batteries in off-grid renewable energy systems," *Solar Energy*, vol. 81, no. 11, pp. 1409-1425, 2007.

[37] M. E. Meral and F. Dincer, "A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 5, pp. 2176-2184, 2011.

[38] N. A. Naamandadin, J. M. Chew, and W. A. Mustafa, "Relationship between Solar Irradiance and Power Generated by Photovoltaic Panel: Case Study at UniCITI Alam Campus, Padang Besar, Malaysia," *Journal of Advanced Research in Engineering Knowledge*, vol. 5, no. 1, pp. 16-20, 2018.

[39] G. K. Singh, "Solar power generation by PV (photovoltaic) technology: A review," *Energy*, vol. 53, pp. 1-13, 2013.

[40] D. Rekioua and E. Matagne, *Optimization of photovoltaic power systems: modelization, simulation and control*, Springer Science & Business Media, 2012.

[41] A. Teke, H. B. Yıldırım, and O. Çelik, "Evaluation and performance comparison of different models for the estimation of solar radiation," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 1097-1107, 2015.

[42] M. E. Meral and F. Dincer, "A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 5, pp. 2176-2184, 2011.

[43] R. Nasrin, M. Hasanuzzaman, and N. A. Rahim, "Effect of high irradiation on photovoltaic power and energy," *International Journal of Energy Research*, vol. 42, no. 3, pp. 1115-1131, 2018.

[44] A. Richmond, "Efficient utilization of high irradiance for production of photoautotropic cell mass: a survey," *Journal of Applied Phycology*, vol. 8, pp. 381-387, 1996.

[45] J. Luke, L. Corrêa, J. Rodrigues, J. Martins, M. Daboczi, D. Bagnis, and J. S. Kim, "A commercial benchmark: light-soaking free, fully scalable, large-area organic solar cells for low-light applications," *Advanced Energy Materials*, vol. 11, no. 9, pp. 2003405, 2021.

[46] H. Mousazadeh, A. Keyhani, A. Javadi, H. Mobli, K. Abrinia, and A. Sharifi, "A review of principle and sun-tracking methods for maximizing solar systems output," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1800-1818, 2009.

[47] F. Zaoui, A. Titaouine, M. Becherif, M. Emziane, and A. Aboubou, "A combined experimental and simulation study on the effects of irradiance and temperature on photovoltaic modules," *Energy Procedia*, vol. 75, pp. 373-380, 2015.

[48] V. Perraki and P. Kounavis, "Effect of temperature and radiation on the parameters of photovoltaic modules," *Journal of Renewable and Sustainable Energy*, vol. 8, no. 1, 2016.

[49] E. M. Vicente, P. dos Santos Vicente, R. L. Moreno, and E. R. Ribeiro, "High-efficiency MPPT method based on irradiance and temperature measurements," *IET Renewable Power Generation*, vol. 14, no. 6, pp. 986-995, 2020.

[50] J. C. Ogbulezie, A. O. Njok, M. K. Panjwani, and S. K. Panjwani, "The impact of high temperature and irradiance source on the efficiency of polycrystalline photovoltaic panel in a controlled environment," *International Journal of Electrical and Computer Engineering*, vol. 10, no. 4, pp. 3942, 2020.

[51] V. H. U. Eze, O. N. Iloanusi, M. C. Eze, and C. C. Osuagwu, "Maximum power point tracking technique based on optimized adaptive differential conductance," *Cogent Engineering*, vol. 4, no. 1, pp. 1339336, 2017.

[52] V. H. U. Eze, U. O. Oparaku, S. A. Ugwu, and C. C. Ogbonna, "A comprehensive review on recent maximum power point tracking of solar photovoltaic systems using intelligent, non-intelligent, and hybrid-based techniques," *International Journal of Innovative Science and Research Technology*, vol. 6, no. 5, pp. 456–474, 2021.

[53] M. C. Eze, V. H. U. Eze, G. N. Ugwuanyi, M. Alnajideen, A. Atia, S. C. Olisa, V. G. Rocha, and G. Min, "Improving the efficiency and stability of in-air fabricated perovskite solar cells using the mixed antisolvent of methyl acetate and chloroform," *Organic Electronics*, vol. 107, pp. 1–10, 2022.

[54] D. H. Li and T. N. Lam, "Determining the optimum tilt angle and orientation for solar energy collection based on measured solar radiance data," *International Journal of Photoenergy*, 2007.

[55] V. H. U. Eze, M. C. Eze, V. Chijindu, C. E. Eze, S. A. Ugwu, and C. C. Ogbonna, "Development of improved maximum power point tracking algorithm based on balancing particle swarm optimization for renewable energy generation," *IDOSR Journal of Applied Sciences*, vol. 7, no. 1, pp. 12–28, 2022.

[56] 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.

[57] M. N. Kamarudin, S. M. Rozali, and M. S. Jamri, "Active cooling photovoltaic with IoT facility," *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 3, pp. 1494, 2021.

[58] S. Nižetić, A. M. Papadopoulos, and E. Giama, "Comprehensive analysis and general economic-environmental evaluation of cooling techniques for photovoltaic panels, Part I: Passive cooling techniques," *Energy Conversion and Management*, vol. 149, pp. 334-354, 2017.

[59] J. Zhang, C. Wang, J. Shi, D. Wei, H. Zhao, and C. Ma, "Solar selective absorber for emerging sustainable applications," *Advanced Energy and Sustainability Research*, vol. 3, no. 3, pp. 2100195, 2022.

[60] R. B. Mansour, M. A. M. Khan, F. A. Alsulaiman, and R. B. Mansour, "Optimizing the solar PV tilt angle to maximize the power output: A case study for Saudi Arabia," *IEEE Access*, vol. 9, pp. 15914-15928, 2021.

[61] R. V. T. K. A. K. L. S. R. Guerrero-Lemus, R. Vega, T. Kim, A. Kimm, and L. E. Shephard, "Bifacial solar photovoltaics–A technology review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1533-1549, 2016.

[62] C. Peike, I. Hädrich, K. A. Weiß, I. Dürr, and F. Ise, "Overview of PV module encapsulation materials," *Photovoltaic International*, vol. 19, pp. 85-92, 2013.

[63] R. K. Varma, *Smart solar PV inverters with advanced grid support functionalities*, John Wiley & Sons, 2021.

[64] X. Zhang, S. K. S. S. Y. Lau, and Y. Zhao, "Photovoltaic integrated shading devices (PVSDs): A review," *Solar Energy*, vol. 170, pp. 947-968, 2018.

[65] Z. Wang, Z. Xu, B. Liu, Y. Zhang, and Q. Yang, "A hybrid cleaning scheduling framework for operations and maintenance of photovoltaic systems," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 52, no. 9, pp. 5925-5936, 2021.

[66] L. M. Peter, "Towards sustainable photovoltaics: the search for new materials," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 369, no. 1942, pp. 1840-1856, 2011.

[67] A. H. Alami, A. G. Olabi, A. Mdallal, A. Rezk, A. Radwan, S. M. A. Rahman, and M. A. Abdelkareem, "Concentrating solar power (CSP) technologies: Status and analysis," *International Journal of Thermofluids*, vol. 18, pp. 100340, 2023.

[68] M. Mussard and M. Amara, "Performance of solar photovoltaic modules under arid climatic conditions: A review," *Solar Energy*, vol. 174, pp. 409-421, 2018.

[69] V. H. U. Eze, "Development of stable and optimized bandgap perovskite materials for photovoltaic applications," *IDOSR Journal of Computer and Applied Science*, vol. 8, no. 1, pp. 44–5, 2023.