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Assessment of Energy Conversion Efficiency in Solar Cells: A Photovoltaic Performance Characterization Study

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Abstract

This study focuses on the assessment of energy conversion efficiency in different types of photovoltaic (PV) solar cells—monocrystalline, polycrystalline, and thin-film—under varying environmental conditions. The research was conducted to evaluate the influence of temperature and light intensity on the performance of these solar cells, aiming to provide insights for optimizing solar energy systems. A three-month field test was conducted where solar cells were exposed to real-world conditions, with data collected on open-circuit voltage (Voc), short-circuit current (Isc), fill factor, maximum power output, and efficiency. Results indicated that monocrystalline cells consistently achieved the highest energy conversion efficiency, reaching 19.1% at 25°C and 80,000 luces, while polycrystalline and thin-film cells demonstrated efficiencies of 18.5% and 17.4%, respectively. The study found that temperature increases negatively impacted efficiency, with monocrystalline cells retaining the highest efficiency under elevated temperatures. These findings are significant for optimizing solar energy systems based on regional environmental factors. The study contributes to ongoing research by providing a comprehensive performance characterization of solar cells under practical conditions, bridging the gap between theoretical models and real-world applications. The results emphasize the need for innovation in solar cell technology to improve performance in high-temperature regions.

Keywords: *Solar cells, energy conversion efficiency, photovoltaic performance, monocrystalline, polycrystalline, thin-film, environmental conditions.*

1. Introduction

The increasing global demand for renewable energy sources has led to heightened interest in solar energy, a critical alternative to fossil fuels. Solar power harnesses energy from the sun, converting it into usable electricity through photovoltaic (PV) cells. These cells have become central to meeting global energy needs in an eco-friendly and sustainable manner. As of 2020, the total installed capacity of solar energy worldwide was estimated to be over 600 GW, with projections showing continued growth driven by both governmental policies and private sector investments (Tripathi, Saxena, & Kumari, 2019). Solar energy's contribution to reducing greenhouse gas emissions and addressing climate change makes it essential for achieving global environmental goals.Photovoltaic cells, which form the backbone of solar energy systems, operate on the principle of converting sunlight directly into electricity. These cells are made of semiconductor materials that generate electric current when exposed to sunlight. The concept of energy conversion efficiency—defined as the ratio of electrical energy output to the incident solar energy—is pivotal in assessing the performance of these cells. Current advancements in material science, design techniques, and energy storage are being driven by the need to maximize the efficiency of solar cells and reduce energy losses (Yamaguchi et al., 2017). The field of photovoltaic technology has evolved over the last few decades, from first-generation silicon-based cells to more advanced third-generation designs that employ organic, dye-sensitized, and perovskite materials (Tanabe, 2007). Despite these advancements, challenges remain in optimizing energy conversion efficiency, as various factors such as light intensity, cell temperature, and the semiconductor materials used impact performance (Srivastava, Gupta, & Singh, 2015). For instance, the maximum theoretical efficiency of a single-junction silicon-based solar cell, also known as the Shockley-Queisser limit, is 33.7% under standard test conditions. However, practical efficiencies achieved by commercially available cells are typically lower, ranging from 15% to 22% depending on the technology used (Chen et al., 2021). In recent years, there has been a growing focus on multi-junction solar cells, which stack multiple layers of different semiconductor materials to capture a broader range of the solar spectrum. These cells have demonstrated much higher efficiencies, with some achieving energy conversion rates of up to 44.4% in laboratory settings (Yamaguchi et al., 2017). While multi-junction cells are highly efficient, their cost and complexity have limited widespread adoption, highlighting the need for further research and innovation in this area. Dimroth and Kurtz (2007) noted that multijunction solar cells hold promise for space applications, where maximizing energy output is critical due to the limited surface area available for solar panels. Moreover, thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) have garnered attention for their potential to offer a lower-cost alternative to silicon-based cells. Although their energy conversion efficiency remains lower than that of crystalline silicon cells, recent developments have shown promising improvements in thin-film technology, with efficiency rates reaching up to 20% under laboratory conditions (Ma et al., 2012). These advancements have opened new avenues for the deployment of solar cells in urban environments, where space and cost considerations are paramount. Another emerging area of research is the use of nanomaterials and up-conversion technologies to improve the efficiency of solar cells. Nanostructures, such as quantum dots and plasmonic nanoparticles, have shown potential for enhancing light absorption and reducing thermal losses in PV cells. Up-conversion materials, which convert low-energy photons into higher-energy ones that can be absorbed by the solar cell, have also been explored as a way to increase the overall energy conversion efficiency of PV systems (Chen et al., 2021). These technologies could lead to a new generation of solar cells with efficiency limits far beyond the current state of the art. The significance of improving energy conversion efficiency in solar cells extends beyond the scientific community. In practical terms, higher efficiency means that fewer solar panels are required to produce the same amount of energy, leading to cost reductions and greater accessibility for residential and commercial users. Furthermore, enhancing the efficiency of solar cells is crucial for expanding their use in energy-intensive sectors such as manufacturing and transportation, where renewable energy adoption is currently hindered by the large surface area required for solar installations (Mansour, 2003). This study aims to assess the energy conversion efficiency of various types of solar cells, focusing on how material composition, environmental factors, and technological innovations influence their performance. By conducting a comprehensive performance characterization, this research seeks to provide valuable insights into the optimization of PV systems, contributing to the ongoing development of more efficient and cost-effective solar energy

2. Literature Review

The energy conversion efficiency of solar cells has been an area of active research due to its importance in enhancing the viability of solar energy as a major renewable energy source. Wang (2022) examined different methods to improve conversion efficiency, including the use of wide-spectrum correspondence and gradient doping. The study found that enhancing light absorption across a broader range of wavelengths significantly impacts the overall efficiency of photovoltaic (PV) cells. This conclusion aligns with the understanding that improvements in material engineering are essential for breaking through current efficiency limits. In another study, Tang (2015) focused on identifying the key challenges in solar cell efficiency, namely the high cost of materials and the difficulty in improving conversion rates. His research proposed using multi-junction cells and advanced material compositions as potential solutions, and these innovations were shown to significantly reduce energy losses while improving efficiency under laboratory conditions. These findings emphasize the continuing importance of material science advancements in driving efficiency improvements. Further developments were noted by Tripathi et al. (2019), who conducted a comparative analysis of different generations of PV cells, from first-generation silicon-based cells to third-generation dye-sensitized and perovskite-based cells. Their study concluded that while first-generation cells remain the most commercially viable due to their robustness, third-generation cells hold the greatest potential for future efficiency improvements. The researchers highlighted that advances in organic and perovskite materials could increase energy conversion rates by over 30% in controlled environments, making them a promising area for future research. A significant theoretical contribution to the field was made by Kita, Harada, and Asahi (2019), who explored the Shockley-Queisser limit, a key parameter in understanding the efficiency constraints of single p-n junction solar cells. Their findings suggested that the maximum theoretical efficiency for these cells is approximately 33.7%, beyond which further improvements would require novel approaches such as multiple carrier excitation, as explored by Tanabe (2007). Tanabe's work introduced the concept of enhanced energy conversion through multiple carrier excitation, which could push efficiency limits to nearly 58% under optimal conditions, opening new avenues for solar cell design. Additionally, Guochang and Guohua (1993) made strides in understanding the role of semiconductor materials in energy conversion efficiency. They developed a new composite material designed for photoelectrochemical (PEC) solar cells, which demonstrated higher efficiency than conventional silicon-based cells in water-splitting experiments. Their findings underscore the importance of ongoing material innovation in achieving the high efficiency required for large-scale solar applications. Recent works have also focused on optimizing external factors that affect solar cell efficiency, such as temperature and light conditions. Srivastava, Gupta, and Singh (2015) identified maximum power point tracking (MPPT) techniques as a crucial element in maintaining high efficiency across a range of environmental conditions. Their study found that cells utilizing advanced MPPT algorithms exhibited up to 25% higher efficiency than those relying on traditional tracking methods. In terms of hybrid systems, Shin et al. (2020) explored the integration of photovoltaic and thermoelectric modules to enhance overall efficiency. Their research demonstrated that cooling the cells led to a significant improvement in energy output, with efficiency increasing from 13.2% to 15% when the cell temperature was reduced from 61°C to 34°C. This result suggests that hybrid systems could be a practical solution for overcoming thermal losses that traditionally reduce PV efficiency in real-world conditions. Chen et al. (2021) explored the application of up-conversion materials to enhance solar cell efficiency by converting low-energy photons into usable energy. Their research demonstrated that these materials could increase the energy conversion rate of PV cells by up to 10% in controlled environments, further highlighting the potential of combining advanced materials with traditional PV systems to enhance overall performance. Finally, Vinay et al. (2024) studies was to improve our knowledge of how modern manufacturing processes and materials impact solar photovoltaic (PV) cell efficiency. It was shown through a methodical experimental examination including several material types and manufacturing procedures that particular approaches and material upgrades had a substantial impact on the performance and efficiency of solar cells. In another article published by Vinay et al. (2024) studied how to use AI and fuzzy logic to maximise solar cell efficiency in real time under changing environmental circumstances. The research sought to overcome the shortcomings of conventional optimisation techniques, which frequently lack real-time flexibility and resilience, by employing a simulation-based methodology with MATLAB/Simulink. With the addition of Genetic Algorithms (GAs), the fuzzy logic-based Maximum Power Point Tracking (MPPT) system showed notable gains in efficiency throughout a range of temperature and sun irradiation circumstances, sustaining MPPT efficiency levels mostly over 85%. While significant progress has been made in improving the energy conversion efficiency of solar cells, a notable gap exists in the comprehensive performance characterization of different types of PV cells under real-world conditions. Most of the existing studies focus on theoretical models and laboratory experiments, which often do not account for the wide range of environmental variables that impact the efficiency of solar cells in practical applications. This study aims to address this gap by conducting a detailed performance characterization of different solar cell types under varying environmental conditions. Understanding the influence of factors such as temperature, light intensity, and material composition on energy conversion efficiency in real-world scenarios will provide valuable insights for optimizing the design and deployment of solar energy systems (Table 1). The findings from this research will contribute to bridging the gap between theoretical efficiency limits and practical performance, ultimately advancing the field of photovoltaic technology. [1-2]

Table 1 Parameters and Description

Parameter	Description
Data Source	Solar Testing Facility
Types of Solar Cells Tested	Monocrystalline Silicon, Polycrystalline Silicon, Thin-Film (Amorphous Silicon)
Testing Duration	3 months
Environmental Factors	Temperature (ranging from 25°C to 50°C), Light Intensity (measured in lux), Humidity
Data Recording Frequency	Every 30 minutes (automated monitoring system)
Performance Parameters	Open-Circuit Voltage (Voc), Short-Circuit Current (Isc), Fill Factor (FF), Maximum Power Output (Pmax), Efficiency (η)
Data Collection Equipment	Solar radiometer (measuring light intensity), thermocouple sensors (recording temperature), digital multimeter (recording voltage and current), data logging system

3. Research Methodology

This study utilizes an experimental research design to evaluate the energy conversion efficiency of different types of photovoltaic (PV) solar cells under varying environmental conditions. The objective is to conduct a comparative performance analysis of monocrystalline silicon, polycrystalline silicon, and thin-film solar cells. Field tests were carried out to assess the impact of temperature, light intensity, and humidity on the efficiency of these solar cells. The data collection spanned a three-month period, with solar cells subjected to real-world environmental conditions. The study recorded performance metrics such as open-circuit voltage, short-circuit current, fill factor, and maximum power output. Data was collected from a dedicated solar testing facility, with solar cells exposed to variable weather conditions. The following table outlines the details of the data collection process:

Data analysis was performed using **MATLAB** software to evaluate the energy conversion efficiency and performance trends of each solar cell type under varying environmental conditions. The following analysis steps were taken:

1. **Data Preprocessing**: Data was cleaned to remove any outliers or inaccuracies.
2. **Efficiency Calculation**: The energy conversion efficiency of each solar cell type was calculated using the equation:

$$\eta = (Pmax \,/\, Ein) \times 100$$

   Where:
   - η is the energy conversion efficiency (%),
   - $Pmax$ is the maximum power output (W),
   - Ein is the incident solar energy (W/m²).
3. **Performance Comparison**: Efficiencies were compared across the three types of solar cells to identify the best-performing type.
4. **Statistical Analysis**: A linear regression model was applied to determine the influence of environmental factors on solar cell performance.

This methodology provided a detailed characterization of solar cell efficiency, allowing for meaningful insights into optimizing solar technology for improved energy conversion under real-world conditions.

4. Results and Analysis

The following tables illustrate the results obtained from the performance evaluation of different types of photovoltaic solar cells (monocrystalline, polycrystalline, and thin-film – Table 2). These tests were conducted at varying temperature levels and light intensities to understand the energy conversion efficiency of each cell type.

Table 2 Solar Cell Performance at 25°C and 80,000 lux

Cell Type	Voc (V)	Isc (A)	Fill Factor	Pmax (W)	Efficiency (%)
Monocrystalline	0.67	8.34	0.81	45.3	19.1
Polycrystalline	0.64	7.89	0.78	42.9	18.5
Thin-Film	0.59	7.11	0.75	39.4	17.4

Interpretation: At 25°C and 80,000 lux, the monocrystalline cells demonstrated the highest efficiency at 19.1%, followed by polycrystalline cells at 18.5%, and thin-film cells at 17.4%. Monocrystalline cells tend to perform better due to their single-crystal structure, which offers higher electron mobility, resulting in improved energy conversion (Table 3).

Table 3 Solar Cell Performance at 35°C and 90,000 lux

Cell Type	Voc (V)	Isc (A)	Fill Factor	Pmax (W)	Efficiency (%)
Monocrystalline	0.65	8.21	0.79	44.2	18.6
Polycrystalline	0.62	7.75	0.76	41.7	18.0
Thin-Film	0.57	6.95	0.73	38.0	16.7

Interpretation: At 35°C and 90,000 lux, the efficiency of all cell types slightly decreased due to the negative impact of rising temperature on the open-circuit voltage (Voc). However, monocrystalline cells still exhibited the highest efficiency, followed by polycrystalline and thin-film cells (Table 4).

Table 4 Solar Cell Performance at 45°C and 100,000 lux

Cell Type	Voc (V)	Isc (A)	Fill Factor	Pmax (W)	Efficiency (%)
Monocrystalline	0.63	8.08	0.77	43.1	18.0
Polycrystalline	0.60	7.60	0.74	40.5	17.3
Thin-Film	0.55	6.79	0.71	37.2	16.3

Interpretation: As the temperature increased to 45°C, a further decline in performance was observed across all cell types. This reduction is due to the inverse relationship between temperature and Voc, with monocrystalline cells remaining the most efficient, albeit with a smaller margin compared to lower temperature scenarios (Table 5).

Table 5 Light Intensity vs. Efficiency at 35°C

Light Intensity (lux)	Monocrystalline (%)	Polycrystalline (%)	Thin-Film (%)
80,000	19.1	18.5	17.4
90,000	18.6	18.0	16.7
100,000	18.0	17.3	16.3

Interpretation: The results indicate that light intensity has a positive correlation with current output, but as temperature rises, the overall efficiency declines. At 100,000 lux, efficiency dropped to 18.0%, 17.3%, and 16.3% for monocrystalline, polycrystalline, and thin-film cells respectively (Table 6).

Table 6 Solar Cell Performance at 30°C and 85,000 lux

Cell Type	Voc (V)	Isc (A)	Fill Factor	Pmax (W)	Efficiency (%)
Monocrystalline	0.66	8.29	0.80	44.9	18.9
Polycrystalline	0.63	7.83	0.77	42.4	18.3
Thin-Film	0.58	7.02	0.74	38.7	17.2

Interpretation: At 30°C and 85,000 lux, the efficiency of monocrystalline cells remained the highest at 18.9%, followed by polycrystalline at 18.3%, and thin-film at 17.2%. The performance differences between the cell types were consistent with previous temperature levels (Table 7).

Table 7 Solar Cell Performance at 40°C and 95,000 lux

Cell Type	Voc (V)	Isc (A)	Fill Factor	Pmax (W)	Efficiency (%)
Monocrystalline	0.64	8.12	0.78	43.5	18.3
Polycrystalline	0.61	7.68	0.75	41.2	17.6
Thin-Film	0.56	6.87	0.72	37.5	16.5

Interpretation: At 40°C and 95,000 lux, all solar cells exhibited lower efficiencies due to the higher temperature. However, monocrystalline cells maintained an efficiency of 18.3%, with polycrystalline and thin-film cells showing respective efficiencies of 17.6% and 16.5%.

5. Discussion

The results of this study provide a comprehensive comparison of the energy conversion efficiency of monocrystalline, polycrystalline, and thin-film solar cells under varying temperature and light intensity conditions. By comparing these findings with existing literature discussed in section 2, it is evident that the experimental results largely align with previous research, while also offering new insights into real-world performance challenges and opportunities.

5.1.Comparison with Literature

As noted in the literature review, Wang (2022) highlighted the importance of material composition and wide-spectrum correspondence for enhancing solar cell efficiency. The current study's findings support this by showing that monocrystalline cells, due to their single-crystal structure, consistently outperform polycrystalline and thin-film cells across all tested environmental conditions. The results from Table 1 demonstrate that monocrystalline cells achieve a peak efficiency of 19.1% at 25°C and 80,000 lux, compared to 18.5% for polycrystalline cells and 17.4% for thin-film cells. This corroborates the conclusions drawn by Tang (2015), who found that monocrystalline cells offer higher electron mobility, thereby improving overall energy conversion. Temperature plays a significant role in solar cell efficiency, as evidenced by the results in Tables 2 and 3. At 35°C and 45°C, the efficiency of all cell types decreases, with monocrystalline cells maintaining the highest efficiency but with a smaller margin of superiority. This result is consistent with Tripathi et al. (2019), who emphasized that higher temperatures negatively impact the open-circuit voltage (Voc) of solar cells, leading to a decline in efficiency. The inverse relationship between temperature and Voc is evident across all three cell types in this study, as shown by the steady decline in Voc values from 0.67 V at 25°C to 0.63 V at 45°C for monocrystalline cells. Thin-film cells, while consistently performing at lower efficiency levels than the crystalline silicon cells, still offer valuable insights into material-specific performance. Thin-film cells, as discussed by Guochang and Guohua (1993), utilize a lower-cost manufacturing process, making them a more affordable option in large-scale applications. However, their performance remains limited, with efficiency values dropping to 16.3% at 100,000 lux and 45°C, as seen in Table 3. While thin-film technologies continue to evolve, the results of this study suggest that their energy conversion efficiency still lags behind more established technologies. The impact of light intensity on energy conversion efficiency was also a focal point of this research, with Table 4 showing the correlation between increased light intensity and higher current output across all cell types. However, as temperature rises, overall efficiency declines. This finding supports Srivastava, Gupta, and Singh (2015), who found that maximum power point tracking (MPPT) techniques can mitigate some of the losses caused by temperature fluctuations. In this study, although monocrystalline cells showed the highest efficiency across all light intensity levels, the relative performance gap between cell types narrowed as light intensity increased. As studies by Vinay (2024), emphasises how crucial real-time flexibility is to optimising renewable energy. A significant benefit over conventional techniques, which might not be as successful in dynamic circumstances, is the fuzzy logic-based system's real-time response to variations in temperature and sun irradiation. He also revealed in another article published that While environmental flexibility was highlighted in perovskite cells, which maintained high efficiency under low light circumstances, key discoveries showed that laser scribing significantly increases the efficiency of silicon-based cells. Significant efficiency gains were also possible with material improvements, like as salt doping in CIGS cells.[3-5]

5.2.Implications of Findings

The results of this study fill a notable gap in the literature by providing real-world performance data for different types of solar cells under varying environmental conditions. While much of the existing research focuses on laboratory settings or theoretical models, this study’s field tests offer a practical perspective on the challenges and opportunities of optimizing solar cell performance in real-world applications. One of the most significant findings of this research is the confirmation that monocrystalline solar cells continue to outperform other types in terms of energy conversion efficiency, particularly under moderate temperatures and high light intensity. The implications for the renewable energy industry are clear: while monocrystalline cells are more expensive to produce, their superior efficiency makes them the most viable option for locations where maximizing energy output is critical. For example, in regions with high solar irradiance and moderate temperatures, such as deserts or coastal areas, monocrystalline cells would offer the best return on investment. Polycrystalline cells, while less efficient, provide a cost-effective alternative for installations where space is not a major constraint. The moderate efficiency drop observed in this study, from 18.5% at 25°C to 17.6% at 40°C, suggests that polycrystalline cells are more suited for applications where temperature control is possible or where temperature fluctuations are minimal. Thin-film solar cells, though the least efficient in this study, continue to hold potential for specific applications, such as building-integrated photovoltaics (BIPV) or in regions where flexibility and lower production costs are prioritized. Thin-film technology's ability to perform in low-light conditions, as suggested by Chen et al. (2021), remains an area worth exploring in future research. While thin-film cells achieved the lowest efficiency in this study, their versatility and cost-effectiveness still make them a strong candidate for certain renewable energy projects.

5.3.Addressing the Literature Gap

This study makes a key contribution by addressing the gap in the literature related to real-world performance characterization of solar cells under varying environmental conditions. As noted in section 2.2, most existing studies rely on theoretical models or laboratory-based experiments, which often do not account for the wide range of environmental variables that impact solar cell efficiency in practical applications. By conducting field tests in different temperature and light intensity settings, this research offers valuable insights into how different solar cell types perform in real-world conditions, where factors such as temperature, humidity, and irradiance fluctuate. The findings of this study provide crucial information for solar energy system designers and policymakers. For instance, in regions where temperature fluctuations are significant, the use of monocrystalline cells may be preferable due to their relatively stable performance across varying environmental conditions. Conversely, in areas with less temperature variation and where cost is a primary concern, polycrystalline or thin-film cells may offer a more affordable solution without a substantial sacrifice in efficiency.[6]

5.4.Significance of the Findings

The significance of these findings extends beyond the scientific community to the renewable energy industry as a whole. As countries around the world continue to increase their investment in solar energy, understanding the real-world performance of different solar cell types will be critical for optimizing energy production. This study demonstrates that environmental factors such as temperature and light intensity have a significant impact on solar cell performance, and the implications of these findings should guide the design and implementation of solar energy systems in various geographic regions. For policymakers, the results of this study underscore the importance of considering environmental conditions when designing solar energy policies. Regions with high temperatures may need to invest in technologies that can mitigate the impact of heat on solar cell efficiency, such as hybrid photovoltaic/thermal systems (Shin et al., 2020). Additionally, efforts to improve cooling mechanisms for solar cells, particularly in regions with extreme temperatures, could enhance overall system performance and increase the viability of solar energy as a major power source.[7-10]

5.5.Future Research Directions

While this study provides valuable insights, it also raises questions for future research. One area that merits further exploration is the development of new materials and technologies to improve the temperature tolerance of solar cells. As demonstrated in this study, temperature is one of the most significant factors affecting energy conversion efficiency, and innovations that reduce the negative impact of heat on solar cell performance would greatly enhance the viability of solar energy systems in hot climates. Additionally, future research should explore the long-term durability and degradation rates of different solar cell types under real-world conditions. While this study focused on short-term performance metrics, understanding how solar cells degrade over time in different environmental conditions will be crucial for optimizing their lifespan and overall efficiency.

Conclusion

The findings of this study highlight significant insights into the energy conversion efficiency of different photovoltaic (PV) solar cells, with a focus on monocrystalline, polycrystalline, and thin-film technologies. Through rigorous testing under varying environmental conditions, including temperature and light intensity, the study demonstrated that monocrystalline cells consistently achieved the highest energy conversion efficiency. Even at higher temperatures, where efficiency generally declines, monocrystalline cells maintained a competitive edge over polycrystalline and thin-film counterparts. The best performance was recorded at 25°C and 80,000 lux, where monocrystalline cells reached a peak efficiency of 19.1%, while polycrystalline and thin-film cells registered 18.5% and 17.4%, respectively. The research also revealed the strong influence of temperature on solar cell performance, validating previous studies that emphasized the inverse relationship between temperature and open-circuit voltage (Voc). As temperatures rose to 45°C, a noticeable decline in efficiency was observed across all solar cell types, with monocrystalline cells retaining their lead but by a narrower margin. These findings suggest that while monocrystalline cells are more resilient to temperature variations, they too are subject to efficiency losses under high-heat conditions. This temperature sensitivity aligns with the broader literature on solar cell performance and suggests that further innovations are necessary to mitigate these losses in real-world applications. A key implication of this study is the importance of selecting appropriate solar cell technology based on the specific environmental conditions of the installation site. For regions with moderate temperatures and high light intensity, monocrystalline cells are the most efficient and cost-effective option due to their superior performance. In contrast, polycrystalline and thin-film cells, though less efficient, may still offer viable alternatives in locations where temperature control or other environmental factors allow for more stable performance. The results of this study will help guide solar energy system designers and policymakers in making informed decisions about technology choices and optimizing installations for maximum energy output. The broader significance of this research lies in its contribution to the ongoing development of solar energy technologies. As countries worldwide increase their reliance on renewable energy, understanding the real-world performance of different solar cell types is critical for ensuring the efficiency and viability of solar energy systems. The study's field tests, conducted over three months in real environmental conditions, provide practical data that can help bridge the gap between theoretical efficiency limits and actual performance. By offering insights into the performance trade-offs between monocrystalline, polycrystalline, and thin-film cells, this research contributes to optimizing solar energy solutions for diverse [11-15] geographical and climatic settings. In conclusion, the findings of this study underscore the need for continued innovation in solar cell technology, particularly in improving temperature tolerance and overall efficiency. The implications for the renewable energy industry are profound, as optimizing the performance of solar cells under varying environmental conditions will be essential for meeting global energy demands sustainably. The results presented here pave the way for future research into material improvements, cooling mechanisms, and long-term performance durability, ultimately contributing to a more sustainable energy future.

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