Performance Comparison of Polycrystalline Solar Cells with and Without Reflectors

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Abstract— This research aims to analyze the comparison of power output between Polycrystalline solar panels with and without the use of mirror reflectors. The growing demand for sustainable energy sources necessitates ongoing efforts to enhance the efficiency of photovoltaic (PV) technology. In this study, a comparative experimental design was implemented over a two-day period, utilizing two identical solar panel configurations: a Reflector Equipped-Solar Panel (RESP) and a Solar Panel Without Reflector (WRSP). The electrical parameters of both configurations, including voltage, current, and power output, along with temperature, were continuously monitored and analyzed. The results indicate that the RESP consistently outperformed the WRSP. On average, the RESP produced 28–35% higher electrical current, which directly translated into a 25–32% increase in power output compared to the WRSP. The peak power of the RESP reached 21.3 W, whereas the WRSP peaked at 16.2 W. Although the RESP operated at a higher temperature (approximately 5–7 °C greater than WRSP), the power gain from increased irradiance effectively outweighed the thermal losses. These findings provide strong empirical evidence that reflective augmentation is a viable and cost-effective method for enhancing the performance of standard solar panels, offering valuable insights for maximizing renewable energy harvesting.

Keywords— Solar Panel; Reflector; Polycrystalline; Power Output.

I. Introduction

The growing global energy demand and the imperative to transition towards sustainable power sources have positioned solar photovoltaic (PV) technology as a cornerstone of future energy landscapes [1]. Among the various types of solar cells, polycrystalline silicon (p-Si) solar cells stand out due to their advantageous balance of cost-effectiveness and reasonable efficiency, making them widely adopted in both residential and commercial applications [2]. However, despite their widespread use, the intrinsic material properties and manufacturing processes of polycrystalline cells inherently limit their maximum achievable efficiency compared to their monocrystalline counterparts [3]. This limitation primarily stems from the presence of grain boundaries within the polycrystalline structure, which can act as recombination centers for charge carriers, thereby reducing power conversion efficiency [4].

To counteract these inherent limitations and further enhance the energy yield of p-Si solar panels, researchers have continuously explored various optimization strategies [5]. One promising avenue involves manipulating the light incident on the solar cell surface to maximize photon absorption [6], [7]. This includes techniques such as anti-reflection coatings [8], [9] and surface texturing [10], [11], which aim to reduce reflection losses and increase the optical path length within the silicon absorber. While these methods have shown significant improvements, there remained potential to further augment the incident light through external means.

Reflective augmentation, often involving the strategic placement of external mirrors or highly reflective surfaces around solar panels [12], [13], offers a compelling approach to capture and redirect additional sunlight onto the active area of the PV module. This technique can effectively increase the irradiance incident on the cell, particularly during off-peak sun hours or in environments where direct sunlight is limited. While the concept of light concentration is not new, its practical application with standard polycrystalline modules, and the precise quantification of its benefits under varying environmental conditions, warranted thorough investigation.

Despite the intuitive benefits of reflective augmentation, a comprehensive and comparative data analysis specifically focusing on the performance of polycrystalline solar cells with and without such augmentation under real-world conditions was notably scarce in existing literature [14]. While some studies touched upon aspects of light concentration or bifacial panels [15], a direct [16], side-by-side empirical comparison [17] that isolated the impact of reflective surfaces on standard polycrystalline cell performance, considering factors like angle of incidence, surface material, and panel orientation, was often generalized or theoretical. This gap in empirical data hindered a precise understanding of the practical gains and optimal implementation strategies for this technology.

Therefore, this research addressed this critical gap by providing a rigorous comparative data analysis of polycrystalline solar cell performance with and without reflective augmentation. The novelty of this study lies in its dedicated focus on systematically quantifying the performance enhancement achieved through the integration of various reflective surfaces with conventional polycrystalline modules. By employing a controlled experimental setup and collecting comprehensive performance data under varying environmental conditions, this research provided empirical evidence for the

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efficacy of reflective augmentation and identified optimal configurations.

This study focuses on standard polycrystalline modules; however, the relative benefit of reflective augmentation may differ for monocrystalline, thin-film, or bifacial technologies. Ultimately, the findings of this study offer valuable insights for solar panel manufacturers, installers, and policymakers, facilitating the design of more efficient and cost-effective solar energy systems. By demonstrating the tangible benefits of reflective augmentation, this research contributes to the broader goal of maximizing renewable energy harvesting, thereby accelerating the transition to a sustainable energy future.

II. METHOD

This study employed a quantitative experimental approach to analyze the comparative power output of polycrystalline solar panels with and without the use of mirror reflectors. The experimental design involved comparing the performance of two identical solar panel configurations under identical environmental conditions. Electrical and temperature data were automatically measured and statistically analyzed to evaluate the effectiveness of mirror reflectors.

A. Experimental System Design

The experimental system was designed to facilitate a direct comparison between a solar panel with and without a reflector. Two identical polycrystalline solar panel units were utilized. One unit, designated as the WRSP (Without Reflector Solar Panel) for both days of testing, served as a control, installed without any additional reflector or cooling. The second unit, designated as the RESP (Reflector Equipped Solar Panel) for both days, was equipped with a mirror reflector positioned to maximize the reflection of sunlight onto the panel's surface. The specific designations for the two configurations across the two-day test are detailed in Table 1.

Both systems were placed at the same location and with identical orientations to ensure uniform solar intensity exposure and minimize the influence of external environmental variables. Although the initial design considered the addition of a cooler to the panel with the reflector, this study focused solely on the impact of the mirror reflector, and thus, cooling was not implemented to isolate the variable. In our current setup the reflector was positioned to redirect additional sunlight onto the solar module surface at a fixed orientation chosen to maximize mid-day irradiance. We recognize that performance is angle-dependent and that optimal reflector angle varies with time of day and season. A detailed three-dimensional (3D) design of the experimental setup, illustrating the precise arrangement of the solar panels and mirror reflectors, is presented in Figure 1.

B. Tools and Materials

The research required a range of tools and materials for the solar panel system configuration and accurate data acquisition. The primary components included two identical polycrystalline solar panel units as the objects of study. For the light-enhanced configuration (RESP), a mirror reflector was used, designed to reflect and direct additional sunlight onto the panel's surface. The reflector used consisted of a flat specular reflective panel (commercial reflective sheet mounted on a rigid backing). Reflector performance depends on shape (flat, parabolic, cylindrical), surface finish (specular vs. diffuse), and material. The data acquisition system was built around an ESP32 microcontroller, serving as the main processing unit. Electrical parameter measurements, specifically voltage and current, were performed using an INA219 sensor integrated with the microcontroller.

TABLE I. SOLAR PANEL CONFIGURATION DESIGNATIONS

Configuration	Designation
Reflector Equipped-Solar Panel Day 1	RESP Day 1
Reflector Equipped-Solar Panel Day 2	RESP Day 2
Solar Panel without Reflector Day 1	WRSP Day 1
Solar Panel without Reflector Day 1	WRSP Day 2

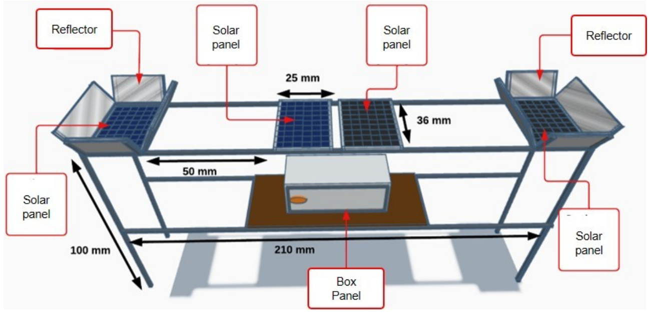

Figure 1. A three-dimensional (3D) design of the experimental setup.

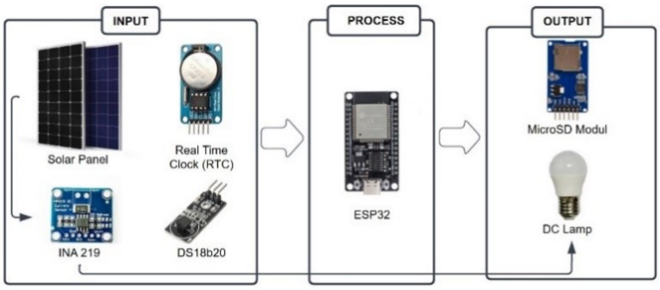

Figure 2. Block diagram of the system

A DS18B20 sensor was employed for continuous monitoring of the solar panel's temperature. To ensure precise time stamping for all collected data, a DS3231 Real Time Clock (RTC) sensor was implemented. All data acquired by the ESP32 were stored locally on a MicroSD Module. In addition to the main electronic components, other supporting materials included a sturdy support structure for positioning the solar panels and reflectors, and appropriate connecting cables for interconnection of the entire system.

C. Data Collection Procedure

The data collection process in this study was automated using a microcontroller-based data acquisition system. The overall process, detailing the input, processing, and output stages, is illustrated in the diagram in Figure 2. As shown, the solar panels (RESP and WRSP), as input, along with the INA219 and DS18B20 sensors, were connected to the ESP32 microcontroller as the processing unit. A Real Time Clock (RTC) sensor was also integrated to provide accurate timestamps for each recorded data point. The data processed by the ESP32 were then stored in the MicroSD Module as output.

In this study both panels were co-located and identically oriented to minimize differences in incident irradiance; however, direct measurements of incident solar irradiance and atmospheric conditions were not recorded. We therefore recognize the potential influence of transient weather (cloud cover, aerosols, humidity) on the measured electrical output. For future experiments we recommend installation of a pyranometer (or calibrated reference cell) to record global horizontal and plane-of-array irradiance, and a meteorological station to log humidity, ambient temperature, and wind speed.

Measured outputs should be normalized to incident irradiance (e.g., W/m²) to isolate configuration-specific performance differences.

Data collection was performed periodically every minute to achieve high data resolution. Measured parameters included voltage (V), current (A), and panel temperature (°C) for both solar panel configurations (RESP and WRSP) over the two-day period. This data acquisition process was conducted daily from 08:00 to 16:00 UTC+7 throughout the testing period. Solar light intensity was not directly measured but was assumed to be relatively uniform for both panels due to their close proximity. It is important to note that while the diagram showed a DC lamp as an output, the focus of this research was on measuring the solar panel's power output itself, not on the electrical load used.

D. Data Analysis

The raw data collected from the MicroSD Module, encompassing temperature, voltage, and current for both the solar panel configurations (RESP and WRSP), were processed and analyzed comprehensively. The initial step in the analysis involved calculating the power output (in Watts) for each recorded data point, using the basic electrical power equation.

Furthermore, descriptive statistical analysis was applied to present the main characteristics of the data, including mean values, standard deviations, and ranges for all measured parameters (temperature, voltage, current, and power). To test the statistical significance of the difference in power output between the two configurations, Analysis of Variance (ANOVA) was employed. The obtained F-statistic was compared with the F-table value at a specific significance level to determine if the observed difference in power output was statistically significant. The results of this analysis provided strong quantitative evidence regarding the effectiveness of using mirror reflectors in enhancing the power output performance of polycrystalline solar panels.

III. RESULTS AND DISCUSSION

A. Results

During the two-day experiment, average global horizontal irradiance recorded at the nearest meteorological station (Tanjungpinang Region, 0–15 min intervals) ranged between 750 and 940 W/m², with peak values near solar noon. Day 1 exhibited slightly higher irradiance stability (average ~890 W/m²) compared with Day 2 (~830 W/m²). Both RESP and WRSP panels received nearly identical exposure due to co-location.

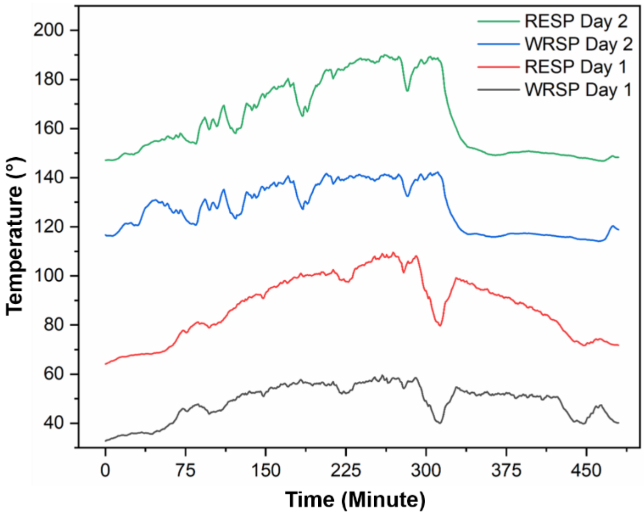

Figure 3. Temperature vs. Time of the RESP and WRSP configurations

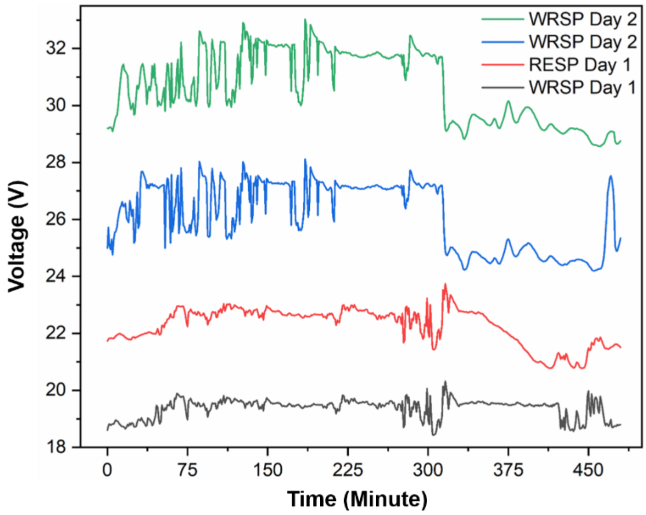

Figure 4. Voltage vs. Time of the RESP and WRSP configurations

The experimental data collected from the two solar panel configurations, the Reflector Equipped-Solar Panel (RESP) and the Without Reflector Solar Panel (WRSP), are presented in the following figures. The results highlight the performance differences between the two setups, particularly concerning temperature, voltage, current, and overall power output over the two-day testing period. The current analysis applies descriptive statistics and ANOVA to compare RESP and WRSP outputs (mean, standard deviation, range). Given the limited number of physical units, the ability to characterize inter-panel variability is constrained.

The relationship between temperature and time for both the RESP and WRSP is illustrated in Figure 3. The graph shows that the RESP consistently maintained a higher temperature than the WRSP throughout the daily testing period from 08:00 to 16:00 WIB. While both configurations exhibit similar fluctuations due to changes in solar intensity, the baseline temperature for the RESP is notably elevated. This is a direct consequence of the mirror reflector, which concentrates additional solar radiation onto the panel, leading to an increase in the energy absorbed and subsequently, a rise in the panel's operating temperature.

Further analysis of the electrical parameters begins with the voltage output, as shown in Figure 4. The voltage profiles for both the RESP and WRSP demonstrate a relatively stable trend over time, with similar fluctuations occurring simultaneously for both configurations. This suggests that while the RESP shows a slight overall increase in average voltage, the voltage output of the solar panels is less significantly impacted by the additional concentrated solar irradiance compared to other parameters.

The small variations observed in both curves are likely attributable to changes in ambient temperature and solar intensity, such as passing clouds, which affect the open-circuit voltage of the PV cells. The electrical current generated by both configurations is depicted in Figure 5. This figure reveals a clear and significant difference in performance. The RESP consistently produced a substantially higher current than the WRSP throughout the testing period on both days. The current profile closely mirrors the daily solar intensity cycle, increasing during the morning and early afternoon before gradually decreasing.

The amplified current output for the RESP is a direct result of the mirror reflector effectively increasing the photon flux incident on the panel's surface, leading to the generation of more charge carriers and, consequently, a higher current. This demonstrates the primary mechanism through which the reflector enhances the electrical performance of the solar panel. Finally, the most critical finding of this study, the electrical power output, is presented in Figure 6. The power output is a function of both voltage and current (P=V×I), and as such, the graph shows a dramatic increase in the power generated by the RESP compared to the WRSP. The power curves closely follow the current trends, indicating that the significant gain in power output is predominantly driven by the increase in current from the reflector [18].

The RESP consistently generated a higher wattage throughout the day, with the peak power output for the RESP being considerably greater than that of the WRSP. This quantitative evidence demonstrates the tangible benefit of using a mirror reflector for augmenting solar panel performance.

B. Analysis of Performance Enhancement

The RESP exhibited higher operating temperatures (observed ~5–7 °C above WRSP) during the measurement period. Because PV cell efficiency decreases with junction temperature, the net power change is the result of two opposing effects: (1) increased photon flux (higher irradiance) raising current and power, and (2) thermal losses reducing cell voltage and conversion efficiency. A quantitative analysis requires simultaneous irradiance and cell-temperature logging; with such data one can estimate the temperature coefficient of power (°C) and perform regression of power versus both irradiance and temperature. This approach will permit explicit quantification of how much of the RESP power gain is attributable to increased irradiance versus how much is offset by temperature-related losses.

The data presented in the results section unequivocally demonstrate that the RESP configuration generated a higher electrical power output compared to the WRSP. This is primarily a function of a substantial increase in the electrical current, as shown in Figure 5. The mirror reflector effectively increased the solar irradiance incident upon the panel's surface [13], leading to a greater number of photons exciting electrons within the polycrystalline cells. This increased photon-to-electron conversion efficiency is the direct cause of the higher current, which, in turn, boosts the overall power output [19]. While Figure 4 shows only a minor increase in voltage for the RESP, it's the significant gain in current that overwhelmingly drives the power enhancement depicted in Figure 6.

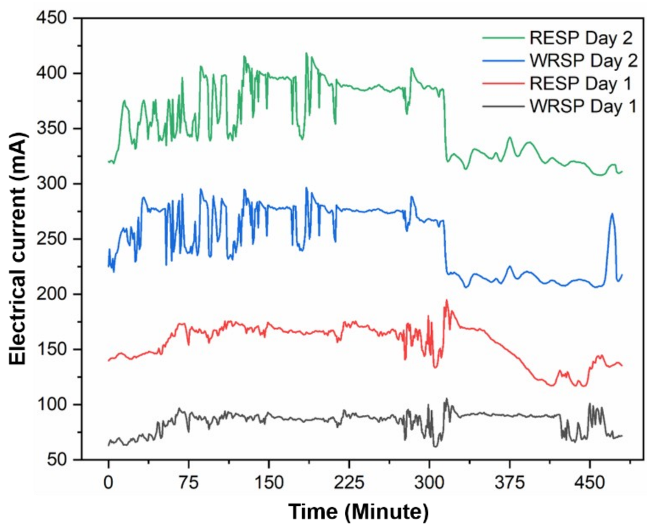

Figure 5. Electrical Current vs. Time of the RESP and WRSP configurations

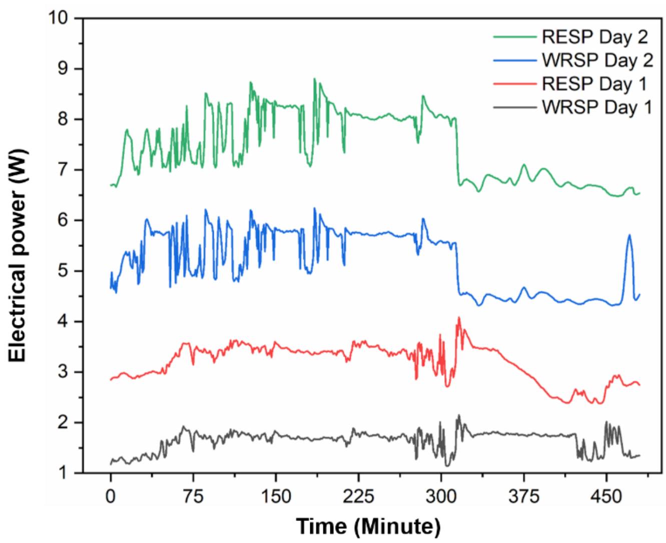

Figure 6. Electrical power vs Time of both the solar panel configurations

A key secondary effect of this concentrated solar irradiance is the increase in the operating temperature of the RESP panel [20], as seen in Figure 3. It's a well-documented physical principle that the efficiency of photovoltaic cells decreases as their temperature rises [21]. However, the observed power output from the RESP still significantly surpasses that of the WRSP, despite operating at a higher temperature. This finding is crucial because it suggests that the power gain from the increased photon flux due to the reflector outweighs the power loss caused by the temperature rise, at least under the conditions of this experiment. The net result is a clear and measurable improvement in energy harvesting [1], [22].

C. Implications and Practical Applications

The findings from this study have significant and practical implications for both residential and commercial solar energy systems. The data provides empirical evidence that a simple and cost-effective physical modification such as the addition of a mirror reflector can tangibly increase the power output of standard solar panels. This method offers a compelling alternative or complements to more expensive efficiency-boosting technologies. For homeowners with limited roof space, for example, a reflector could maximize the energy generation from a smaller number of panels. For large-scale solar farms, this approach could be used to optimize energy yield, especially during periods of lower sun angle.

Beyond simple power gains, the data-centric nature of this analysis also provides a foundation for future optimization. By demonstrating that current is the primary beneficiary of the reflector, future designs can focus on maximizing this effect while mitigating the negative impact of heat. The success of this straightforward augmentation technique could accelerate the adoption of solar technology by making it more efficient and a more attractive investment. By maximizing the energy generated from existing hardware, we move closer to the goal of a sustainable energy future.

While this study demonstrates clear short-term power improvements with reflective augmentation, a rigorous economic assessment is needed to determine feasibility for widespread deployment. Key economic inputs include the cost of reflector materials and installation, incremental maintenance costs (cleaning and repairs), and the additional energy yield (kWh/year). We recommend conducting a dedicated Levelized Cost of Energy (LCOE) and payback-period analysis in future work that uses measured energy gains (normalized to irradiance and operational hours), local electricity tariffs, and maintenance schedules to quantify net economic benefit.

The benefit of reflective augmentation will depend strongly on site-specific factors such as latitude (affecting sun path and low-angle hours), typical cloudiness, and ground albedo. Reflectors are expected to provide greater relative gains in locations or seasons with low sun angles (e.g., high latitudes during shoulder seasons) or where additional direct irradiance can be redirected efficiently. Conversely, in persistently overcast or highly humid climates, gains may be muted. We therefore recommend replication of experiments across diverse climatic regions to develop deployment guidelines tailored to geographic conditions. Practical adoption of reflector systems depends not only on technical performance but also on user acceptance factors such as aesthetics, perceived glare, and installation complexity.

D. Limitations and Future Work

While this study provides valuable data on the performance of reflective augmentation, it's important to acknowledge its limitations. The experiment was conducted in a specific location and over a limited two-day period. This means the results may not be directly transferable to all geographic locations, which have different climate conditions, solar intensity profiles, and seasons.

Additionally, the analysis did not consider the potential long-term effects of the sustained higher operating temperature on the solar panel's degradation or lifespan. Over time, this could impact the overall return on investment. These limitations present clear opportunities for future research. Subsequent studies should be conducted over longer periods to better understand the long-term performance and durability of the RESP configuration. It would also be highly valuable to replicate this experiment in different climate zones to see how the results vary. Furthermore, future work could explore the optimal angles and materials for the reflector, or even integrate active cooling systems to counteract the temperature increase and potentially achieve even greater efficiency gains.

This study presents an initial, controlled comparative experiment using two identical polycrystalline modules measured over a two-day period. We acknowledge that this sample size and short duration limit the statistical power and generalizability of the results. Future studies should expand the experimental scope by including multiple replicate panels for each configuration (recommended: ≥5 replicates per configuration), deploying tests over longer periods (recommended: multi-week to multi-season campaigns), and performing power analyses prior to data collection to ensure sufficient statistical sensitivity. Such expansions will enable more robust variance estimates and strengthen inferential conclusions.

Reflector-equipped systems introduce additional operational considerations such as cleaning frequency (dust and soiling), mechanical wear of mounting hardware, susceptibility to wind loading, and the risk of misalignment over time. Future field trials should include maintenance logs, periodic alignment checks, and structural assessments to quantify downtime and maintenance costs. Monitoring should also track how soiling and surface abrasion affect reflectivity and consequent power output. Additionally, future experiments should perform angle-sweep tests (e.g., 0°–60° in 5° increments relative to the module plane) and evaluate performance under clear and diffuse sky conditions to identify angle–performance curves and dynamic/seasonal setpoints.

To evaluate whether reflector-induced gains are sustainable, long-term field monitoring (seasonal to multi-year) is required. Future protocols should include periodic I–V curve tracing, capacity-factor monitoring across seasons, scheduled visual inspections for material degradation, and accelerated aging tests (thermal cycling, UV exposure) in the laboratory. These procedures will clarify whether short-term power gains translate into meaningful long-term energy yield improvements or whether accelerated ageing reduces net benefits.

It is important to evaluate whether reflector deployment accelerates degradation of modules (e.g., due to higher operating temperatures or microclimatic effects). We recommend joint lifespan studies that include accelerated thermal cycling, damp–heat exposure, UV-weathering tests, and periodic electrical performance tracking (I–V curves) to quantify any changes in degradation rates when panels operate with reflectors versus without. We therefore recommend that future studies include direct side-by-side comparisons across PV technologies to determine whether reflectors provide proportionally greater benefit for lower-efficiency modules or whether bifacial modules already capture similar gains from ground-reflected irradiance.

IV. Conclusion

In conclusion, this study experimentally demonstrated that a mirror reflector can enhance the electrical performance of a polycrystalline solar panel under identical operating conditions. The Reflector-Equipped Solar Panel (RESP) produced consistently higher current and power output than the Without-Reflector Solar Panel (WRSP) across the two-day test period, with average power gains of approximately 25–32 %. The increase in current was the primary factor responsible for this improvement, while the voltage increase remained modest. The RESP also operated at a higher surface temperature (about 5–7 °C above WRSP), indicating a trade-off between enhanced irradiance and thermal effects. Within the scope of this short-term experiment, reflective augmentation proved to be a simple and cost-effective means of improving instantaneous energy yield. However, further work involving longer-term measurements, direct irradiance monitoring, economic evaluation, and diverse climatic conditions is necessary to validate its broader applicability and sustainability.

References

[1] S. Awad, A. Alzahrani, E. E. Abdel-Hady, and W. M. Mohammed, ‘Revolutionizing the Global Energy Landscape: The Impact of Renewable Energy Technologies’, in *Renewable Energy Technologies and Strategies in the Global Energy Transition*, ACS Publications, 2025, pp. 39–58.

[2] V. Rathinavelu *et al.*, ‘Texturing of silicon nitride passivation layers on functional behaviour study of polycrystalline silicon (p-Si) made with plasma enhanced chemical vapour deposition’, *J. Mater. Sci. Mater. Electron.*, vol. 36, no. 1, p. 73, 2025.

[3] C. Zhou *et al.*, ‘Polycrystalline SnSe with a thermoelectric figure of merit greater than the single crystal’, *Nat. Mater.*, vol. 20, no. 10, pp. 1378–1384, 2021.

[4] J. Quirk, M. Rothmann, W. Li, D. Abou-Ras, and K. P. McKenna, ‘Grain boundaries in polycrystalline materials for energy applications: First principles modeling and electron microscopy’, *Appl. Phys. Rev.*, vol. 11, no. 1, 2024.

[5] A. M. Soomar, A. Hakeem, M. Messaoudi, P. Musznicki, A. Iqbal, and S. Czapp, ‘Solar photovoltaic energy optimization and challenges’, *Front. Energy Res.*, vol. 10, p. 879985, 2022.

[6] N. Chuchvaga, N. Aubakirova, N. Tokmoldin, V. Klimenov, and D. W. Boukhvalov, ‘A Comprehensive Approach to Optimization of Silicon-Based Solar Cells’, *Surfaces*, vol. 7, no. 4, pp. 951–968, 2024.

[7] S. R. Mirnaziry, M. A. Shameli, and L. Yousefi, ‘Design and analysis of multi-layer silicon nanoparticle solar cells’, *Sci. Rep.*, vol. 12, no. 1, p. 13259, 2022.

[8] P. Zala *et al.*, ‘Optimizing anti-reflection coating using electrochemical impedance spectroscopy to enhance electrical performance of solar cell’, *Opt. Quantum Electron.*, vol. 57, no. 8, pp. 1–19, 2025.

[9] S. Maqsood *et al.*, ‘Assessment of different optimized anti-reflection coatings for ZnO/Si heterojunction solar cells’, *Ceram. Int.*, vol. 49, no. 23, pp. 37118–37126, 2023.

[10] K. Choubani *et al.*, ‘Enhancing Optoelectronic Properties of Multicrystalline Silicon Using Dual Treatments for Solar Cell Applications’, *Inorganics*, vol. 13, no. 5, p. 142, 2025.

[11] F. A. H. Mutlak, A. F. Ahmed, U. M. Nayef, Q. Al-zaidi, and S. K. Abdulridha, ‘Improvement of absorption light of laser texturing on silicon surface for optoelectronic application’, *Optik (Stuttg).*, vol. 237, p. 166755, 2021.

[12] M. A. Zahid, H. Yousuf, Y. Kim, J. Yi, and S. K. Dhungel, ‘A novel approach for power enhancement of vertical mounted bifacial photovoltaic system using reflecting mirrors’, *J. Clean. Prod.*, vol. 397, p. 136541, 2023.

[13] M. K. Kolamroudi, M. Ilkan, F. Egelioglu, and B. Safaei, ‘Maximization of the output power of low concentrating photovoltaic systems by the application of reflecting mirrors’, *Renew. Energy*, vol. 189, pp. 822–835, 2022.

[14] T. Ahmed and M. K. Das, ‘Enhanced efficiency in thin film solar cells: optimized design with front nanotextured and rear nanowire-based light trapping structure’, *IEEE Trans. Nanotechnol.*, vol. 23, pp. 456–466, 2024.

[15] Y. Zhang, J. Q. Gao, Y. Yu, Q. Shi, and Z. Liu, ‘Influence of incidence angle effects on the performance of bifacial photovoltaic modules considering rear-side reflection’, *Sol. Energy*, vol. 245, pp. 404–409, 2022.

[16] J. M. Saura, P. M. Rodrigo, F. M. Almonacid, D. Chemisana, and E. F. Fernández, ‘Experimental characterisation of irradiance and spectral non-uniformity and its impact on multi-junction solar cells: Refractive vs. reflective optics’, *Sol. Energy Mater. Sol. Cells*, vol. 225, p. 111061, 2021.

[17] G. Badran and M. Dhimish, ‘Comprehensive study on the efficiency of vertical bifacial photovoltaic systems: a UK case study’, *Sci. Rep.*, vol. 14, no. 1, p. 18380, 2024.

[18] S. Ibrahim Mohammad *et al.*, ‘Numerical investigation of thermal-electrical performance in solar modules using hybrid, parabolic, and flat-plate reflectors’, *Energy Explor. Exploit.*, p. 01445987251361165, 2025.

[19] P. K. Tawalare, ‘Optimizing photovoltaic conversion of solar energy’, *AIP Adv.*, vol. 11, no. 10, 2021.

[20] L. M. Shaker, A. A. Al-Amiery, M. M. Hanoon, W. K. Al-Azzawi, and A. A. H. Kadhum, ‘Examining the influence of thermal effects on solar cells: a comprehensive review’, *Sustain. Energy Res.*, vol. 11, no. 1, p. 6, 2024.

[21] C. Sun, Y. Zou, C. Qin, B. Zhang, and X. Wu, ‘Temperature effect of photovoltaic cells: a review’, *Adv. Compos. Hybrid Mater.*, vol. 5, no. 4, pp. 2675–2699, 2022.

[22] A. I. Vlasov, E. S. Bezborodov, and I. K. Naumov, ‘Energy-Efficient Internet of Things Technology Networks Based on the LoRa Communication Module’, in *2025 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, IEEE, 2025, pp. 6–11.