

Comparative Performance Analysis of Monocrystalline Silicon Solar Cells Under Fresnel Lens Concentration and Direct Sunlight

*Yusuf Mohammad Chindo, ¹Ali Alibe Mustapha, ¹Ahmed Musa Jatto, ¹Abubakar A. Janga, ²Usman Mohammed

¹Department of Mechanical Engineering Technology, The Federal Polytechnic Damaturu, Damaturu, Yobe State.

²Department of Agricultural and Bio-Environmental Engineering Technology, Federal Polytechnic Bali, Taraba state.

*Corresponding author: Ymchindo02@gmail.com

ABSTRACT

As global demand for sustainable energy solutions intensifies, improving the efficiency-to-cost ratio of solar photovoltaic (SPV) technologies has become a critical priority. This study presents an experimental evaluation of a Low-Concentration Photovoltaic (LCPV) system designed to enhance the performance of monocrystalline silicon solar cells using a cost-effective, spot-focus Fresnel lens. Unlike conventional High-Concentration Photovoltaic (HCPV) systems that rely on complex cooling and precise sun-tracking mechanisms, this research explores a simplified approach by optimizing the distance between the lens and the receiver, efficiently "defocusing" to balance power generation with thermal management. The experimental results demonstrate that integrating the polyvinyl chloride (PVC) Fresnel lens significantly alters the system's electrical characteristics compared to non-concentrated direct sunlight. The proposed LCPV setup achieved an approximately 45% increase in relative power output. This performance boost was driven by a substantial rise in short-circuit current (I_{sc}) and a modest improvement in open-circuit voltage (V_{oc}). Furthermore, the Fill Factor (FF) increased from **0.56 to 0.59**, indicating improved charge carrier collection and reduced relative resistive losses under concentrated irradiation. These findings confirm that low-concentration systems offer a scalable, economically viable alternative to high-precision concentrators, providing significant efficiency gains with reduced mechanical complexity.

Keywords: *Low-Concentration Photovoltaics (LCPV), Fresnel Lens Concentrator, Monocrystalline Silicon Solar Cell, Solar Energy Efficiency, Fill Factor Optimization, Photovoltaic Thermal Management.*

1. INTRODUCTION

Renewable energy is becoming one of the essential zero-emission sources to meet worldwide energy needs and to address the rapid depletion of fossil fuels, which has a major impact on global warming (Roy et al., 2023). As the world's demand for clean energy escalates, particularly for sustainable power solutions, renewable energy's highly advanced efficiency technologies have become indispensable for the energy transition (Liu et al., 2025). Solar photovoltaic (SPV) technology is one of the most attractive renewable energy options for electricity generation due to its advantages over other technologies and its environmental friendliness. Crystalline Silicon is the main component used in the fabrication of solar cells in SPV technology, in which the Sun's light energy is converted into electrical energy, and research continues worldwide into ways and means of producing highly efficient, low-cost solar cells (Tian et al., 2025).

Silicon-based solar photovoltaic technology is becoming an important renewable energy option for meeting future power needs, but reducing its cost remains a major challenge (Osman & Qureshi, 2025). Cost can be lowered in several ways, such as improving cell efficiency, enhancing light trapping, using thinner wafers, adopting thin-film technologies, or applying concentrator photovoltaic (CPV) systems (Nandurkar et al., 2025). In CPV systems, sunlight is concentrated onto a smaller cell area, reducing the required module area and significantly cutting overall system cost. As a result, extensive research has focused on CPV designs using different lenses or mirrors, cell materials, cooling methods, and tracking approaches (Xu et al., 2022). Although very high efficiencies have been achieved in laboratories, especially with advanced multi-junction cells,

these systems are expensive and require extremely high concentration ratios and precise sun-tracking. Such strict accuracy in manufacturing, installation, and operation increases system complexity and cost, making practical and affordable implementation a key challenge (Abd-Elhady et al., 2025).

This study experimentally evaluates a Low-Concentration Photovoltaic (LCPV) system equipped with a spot-focus Fresnel lens. Rather than limiting cell placement to the exact focal point, the research investigates electrical performance at different distances to maximize power output and reduce thermal degradation.

2. LITERATURE REVIEW

2.1 Evolution of Concentrator Photovoltaic Systems

The increasing interest in cost-effective solar energy conversion has driven significant research into concentrator photovoltaic (CPV) technologies over the past four decades. CPV systems operate on the fundamental principle of using optical elements to focus sunlight onto smaller, high-efficiency solar cells, thereby reducing the semiconductor area required for a given power output and potentially lowering overall system costs (El Alami et al., 2024). These systems are generally classified based on their concentration ratio into low-concentration (LCPV, 1–40 suns), medium-concentration (40–300 suns), and high-concentration (HCPV, >300 suns) categories (Li et al., 2025).

Diachronically, HCPV systems utilizing multi-junction solar cells have demonstrated remarkable laboratory efficiencies exceeding 40%, making them attractive for utility-scale applications. However, these systems require precise sun-tracking mechanisms, sophisticated thermal management, and high-accuracy optical

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components, which substantially increase manufacturing, installation, and operational complexity. The stringent alignment tolerances and associated costs have limited widespread adoption of HCPV technology, particularly in decentralized or small-scale applications (Naaz et al., 2025).

2.2 Fresnel Lenses in Solar Concentration Applications

Among the available optical concentrators, Fresnel lenses have emerged as a preferred choice for CPV applications due to their unique combination of optical performance and practical advantages. Unlike conventional curved lenses, Fresnel lenses achieve concentration through a series of concentric grooves that approximate the curvature of a standard lens while significantly reducing material volume and weight. This design characteristic makes them particularly suitable for photovoltaic applications where structural simplicity and cost minimization are paramount (De et al., 2025).

According to H. Huang et al., (2025). They investigated non-tracking low-concentration systems employing Fresnel lenses and demonstrated that careful optical design could achieve effective concentration ratios of $2\times$ - $10\times$ without the need for continuous solar tracking. Their research highlighted that PVC-based Fresnel lenses, despite having lower optical transmission than glass alternatives, offer adequate performance for LCPV applications while providing substantial weight reduction and manufacturing cost benefits. The groove pitch and focal length parameters, as specified in the present study (0.3 mm and 300 mm, respectively), align with optimal configurations identified in prior research for achieving uniform flux distribution at the receiver plane.

2.3 Performance Characteristics of Monocrystalline Silicon Under Concentration

Monocrystalline silicon solar cells remain the dominant technology in photovoltaic markets due to their established manufacturing processes, reliability, and well-understood performance characteristics (Mostafa et al., 2025). Under concentrated illumination, silicon cells exhibit distinct behavioral changes in their electrical parameters. The short-circuit current (I_{sc}) increases approximately linearly with concentration ratio, as it is directly proportional to the incident photon flux (Han et al., 2024). Conversely, the open-circuit voltage (V_{oc}) increases logarithmically with concentration, following the diode equation relationship:

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{J_{ph}}{J_0} + 1 \right)$$

This logarithmic dependence means that while V_{oc} improves with concentration, the gains diminish at higher concentrations. Chen and Li (Cheng & Lin, 2025) reviewed the performance of silicon-based CPV systems and noted that optimal concentration ratios for crystalline silicon typically range from 2 to 20 suns, beyond which series resistance losses and thermal effects begin to dominate, potentially negating efficiency gains.

2.4 Thermal Management Challenges in Concentrated Systems

The thermal behavior of solar cells under concentrated illumination represents a critical consideration in CPV system design. As incident energy density increases, a substantial portion of the absorbed radiation is converted into heat, raising the cell temperature and potentially degrading electrical performance (Chen et al., 2023). As argued by (Pera et al., 2023) They conducted a comprehensive review of cooling

techniques for CPV systems, identifying passive, active, and hybrid approaches for thermal management. Their analysis concluded that while active cooling systems offer superior temperature control, they introduce additional parasitic power consumption and mechanical complexity that may be unsuitable for small-scale or cost-sensitive applications.

The temperature sensitivity of silicon solar cells manifests most significantly in the open-circuit voltage, which decreases by approximately 2.3 mV/°C for crystalline silicon devices. This thermal degradation effect partially offsets the electrical gains from increased illumination, creating a design trade-off between concentration ratio and operating temperature. El Alami et al. emphasized that effective CPV system design must balance optical concentration with thermal dissipation capabilities to maintain optimal operating temperatures (Zhou et al., 2023).

2.5 Low-Concentration Photovoltaic Systems: A Practical Alternative

Recent research has increasingly focused on LCPV systems as a pragmatic compromise between the complexity of HCPV and the moderate efficiency of flat-plate installations. According to (J. Huang et al., 2026) The seasonal performance of photovoltaic cells under standard and concentrated conditions, finding that LCPV configurations could achieve significant power gains without requiring the precision-tracking mechanisms essential for high-concentration operation. Their work demonstrated that concentration ratios of 2–10 suns could be achieved with simplified optical alignment and minimal tracking requirements.

The concept of "defocusing" or operating at distances away from the exact focal point, as explored in the present study, represents an

innovative approach to managing the thermal-electrical trade-off in LCPV systems. By positioning the receiver at distances greater than or less than the nominal focal length, the incident flux density can be moderated while still achieving concentration above non-concentrated levels (Ismail et al., 2026). This technique allows system designers to select operating points that maximize net power output by balancing increased photocurrent against reduced thermal voltage.

2.7 Research Gap and Contribution of the Present Study

Although extensive literature exists on both HCPV systems and flat-plate silicon photovoltaics, comparatively little attention has been paid to optimizing LCPV configurations using commercially available materials and simplified mechanical arrangements (Gebreabe et al., 2026). The majority of CPV research emphasizes either ultra-high-efficiency multi-junction cells that require precise tracking or theoretical optical modeling without experimental validation under realistic operating conditions.

In-line with the above, previous investigations have typically positioned receivers strictly at the focal point to maximize instantaneous concentration, often overlooking the practical benefits of controlled defocusing for thermal management (Ribeiro et al., 2026). The interaction between receiver position, electrical performance, and thermal behavior in PVC Fresnel lens systems remains underexplored, particularly for monocrystalline silicon cells in low-concentration regimes.

The present study addresses these gaps by experimentally evaluating an LCPV system that prioritizes practical implementability alongside

performance enhancement. By systematically varying the lens-receiver distance and characterizing the resulting electrical parameters, this research provides empirical data on the performance trade-offs inherent in simplified concentrator systems. The use of readily available PVC Fresnel lenses and standard monocrystalline cells ensures that findings are relevant to real-world applications where cost and complexity constraints govern technology adoption decisions

3. MATERIALS AND METHODS

3.1 Materials and Material Selection

The Monocrystalline silicon solar cells were selected as the energy conversion material due to their high efficiency, thermal reliability, and widespread use in photovoltaic energy systems. The cells, sourced from a practical laboratory, are circular with a diameter of 10.0 cm and deliver a maximum output of 0.5 V and 1.0 A, corresponding to a peak power of 1 W under standard test conditions. From an energy systems perspective, monocrystalline silicon provides a stable electrical response and consistent performance under concentrated solar irradiation, making it appropriate for coupling with optical concentrators.

The optical concentrating element employed in this study is a Fresnel lens, selected for its high concentration capability, low mass, and reduced material usage compared to conventional curved lenses. The lenses were obtained from the Shema Energy Research Center and are manufactured from polyvinyl chloride (PVC), a material chosen for its lightweight nature, cost-effectiveness, ease of machining, and adequate optical transmission for solar applications. Each lens has dimensions of 218 mm × 156 mm × 0.4 mm, providing an effective aperture area approximately four times that of the photovoltaic cell, thereby increasing

the incident solar energy. The lens features a groove pitch of 0.3 mm and a focal length of 300 mm, parameters selected to ensure efficient light concentration while maintaining manageable thermal and mechanical constraints.

3.2 Solar concentrator selection

The selection of the solar concentrator was guided by mechanical design requirements and energy conversion efficiency. Various concentrator configurations were evaluated with respect to their geometrical form, optical concentration capability, structural simplicity, and compatibility with the receiver placement. In mechanical and energy systems, concentrator performance is strongly governed by geometry-dependent parameters such as concentration ratio, focal length, and alignment tolerance.

Over the past four decades, advances in solar concentrator design have focused primarily on improving optical efficiency while reducing structural complexity and material cost. Among available designs, those that achieve effective solar flux concentration with minimal mechanical complexity have shown the greatest practical relevance. Consequently, the concentrator selected in this study emphasizes optical effectiveness, mechanical stability, ease of fabrication, and material availability, making it suitable for experimental evaluation and scalable energy applications.

In general, the chosen materials and concentrator configuration reflect a balanced approach that integrates mechanical design considerations, energy-conversion efficiency, and material feasibility, aligning with the requirements of experimental solar energy systems and mechanical engineering applications.

3.3 Overview of Solar Cell Parameters

This section outlines the key electrical characteristics used to evaluate the performance of silicon solar cells.

A. Open Circuit Voltage (V_{oc})

The Open Circuit Voltage is the maximum voltage a solar cell can generate when it is not connected to any external circuit (meaning zero current is flowing)². It represents the potential difference between the terminals when the cell is "open." Importantly, V_{oc} is sensitive to heat; as the temperature increases, the voltage decreases.

The relationship is described by the equation:

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{J_{ph}}{J_0} + 1 \right) \dots \dots \dots \text{eqn (1)}$$

Where;

k = the Boltzmann constant,

T = temperature,

q = electronic charge,

J_{ph} = Photocurrent, and

J_0 = Saturation current

B. Short Circuit Current (I_{sc})

This is the maximum current a solar cell can produce. It occurs when the positive and negative terminals are connected directly (shorted), reducing the voltage to zero. Unlike voltage, the short-circuit current is primarily determined by the intensity of light striking the cell.

It is calculated as:

$$I_{sc} = qG (L_n + L_p) \dots \dots \dots \text{eqn (2)}$$

Where;

G = generation rate, and

L_n / L_p = diffusion length

C. Fill Factor (FF)

The Fill Factor is a measure of the "quality" or "squareness" of the solar cell's performance curve. It compares the *actual* maximum power the cell produces (P_{max}) to the *theoretical* limit ($V_{oc} + I_{sc}$)

Graphically, it represents the area of the largest rectangle that can fit under the Current-Voltage (IV) curve. A higher Fill Factor indicates a more efficient cell, with typical high-quality values ranging from 0.75 to 0.85.

$$FF = \frac{V_{max} \times I_{max}}{V_{oc} \times I_{sc}} \dots \dots \dots \text{eqn (3)}$$

D. Efficiency (η)

Efficiency measures how well the solar cell converts sunlight into electricity. It is the ratio of the electrical power output to the solar energy input. Standard testing assumes an incoming solar intensity (P_{in}) of 1000 W/m.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{max} \times I_{max}}{P_{light}} \dots \dots \dots \text{eqn (4)}$$

3.4 Experimental Setup

The study utilized a monocrystalline silicon solar cell with a diameter of 10.0 cm. The manufacturer-rated specifications for the cell were a maximum voltage (V_{max}) of 0.5 V, maximum current (I_{max}) of 1.0 A, and optimal power of 1 W. The optical concentrator was a PVC Fresnel lens with dimensions 218 mm × 156 mm × 0.4 mm and a groove pitch of 0.3 mm⁸. The focal length (f) of the lens was determined to be 300 mm (30 cm)⁹.

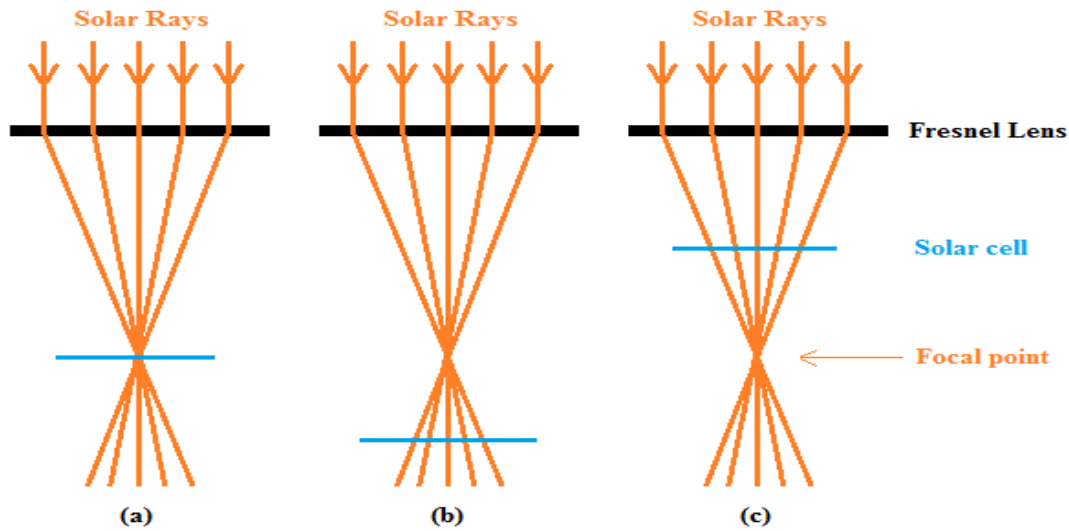


Fig. 1 (a) solar cell at the focal point ($1.0F$), (b) solar cell below the focal point ($>1.0F$), and (c) solar cell above the focal point ($<1.0F$).

3.5 Data Collection Protocol

Measurements were conducted in three distinct stages:

1. **Laboratory Simulation:** A sodium light source was used to establish baseline current-voltage (I-V) responses under varying light intensities.
2. **Direct Sunlight (No Concentrator):** The solar panel was exposed to outdoor solar radiation. Voltage and current were recorded sequentially to assess the cell's stability under natural heating.
3. **Concentrated Sunlight (Fresnel Lens):** The Fresnel lens was positioned above the solar cell. To investigate the effects of concentration and distance, readings were taken at varying heights (from 10 cm to 90 cm) rather than strictly at the focal point.

4.0 RESULTS

4.1 Laboratory characterization of solar cell performance under sodium light illumination

Table 1: Current-Voltage (I-V) characteristics measured under sodium light illumination.

Light Setting (Step)	Current (A)	Voltage (V)	Power (W)
1.0	0.08	11.62	0.93
1.5	0.16	14.07	2.25
2.0	0.34	16.95	5.76
2.5	0.54	18.24	9.85
3.0	0.76	18.95	14.40
3.5	0.90	19.37	17.43
4.0	1.06	19.79	20.98
4.5	1.16	19.99	23.19
5.0	1.24	25.20	31.25

4.2 Performance Characterization Under Direct Natural Sunlight

Table 1 presents the laboratory characterization of solar cell performance under sodium light illumination, while Table 2 displays the performance characterization under direct natural sunlight.

2.5	0.28	20.20	5.66
3.0	0.27	20.50	5.54
3.5	0.25	20.30	5.10
4.0	0.23	20.10	4.62
4.5	0.21	19.97	4.20
5.0	0.20	19.95	4.00

Table 2: Current-Voltage parameters measured under non-concentrated solar irradiation

Light Setting (Step)	Current (A)	Voltage (V)	Power (W)
1.0	0.30	22.80	6.84
1.5	0.33	21.50	7.10
2.0	0.35	20.60	7.21

5. DISCUSSION

The application of the Fresnel lens significantly altered the performance characteristics. Unlike the direct sunlight test, the LCPV setup showed a consistent increase in power output as the distance from the lens was adjusted.

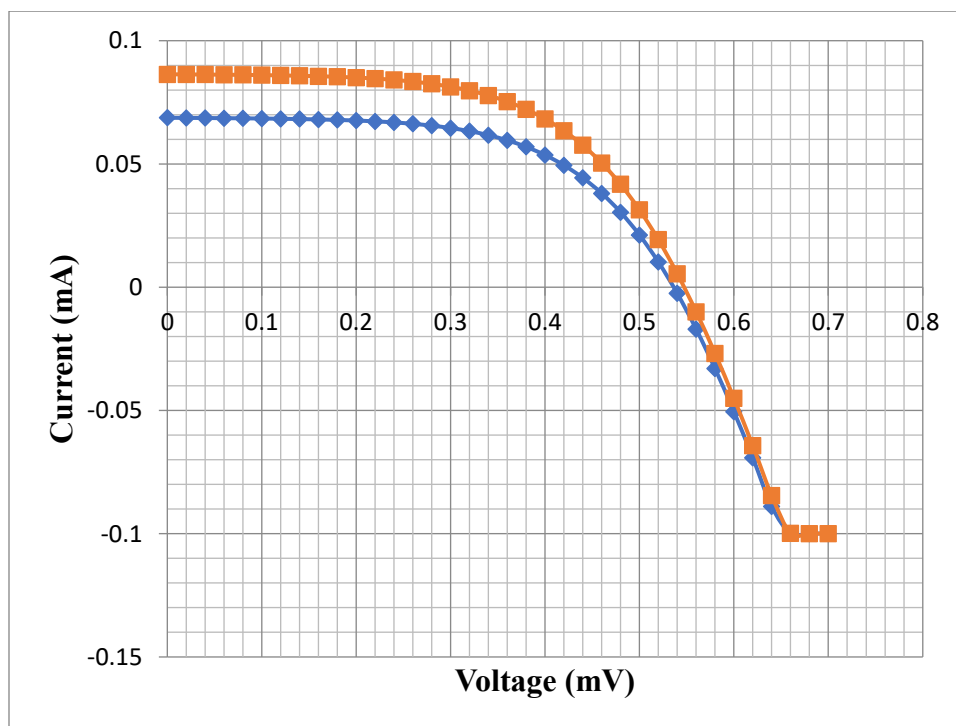


Fig 2. Comparative analysis of characteristics with and without a Fresnel lens

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Table 3. Results of comparative analysis of characteristics of with and without a Fresnel lens

Parameter	Blue Curve (Without / Lower Concentration)	Orange Curve (With / Higher Concentration)
Short-circuit current (I_{sc})	≈ 0.065 mA	≈ 0.085 mA
Open-circuit voltage (V_{oc})	≈ 0.55 V	≈ 0.58 V
Voltage at MPP (V_{mp})	≈ 0.45 V	≈ 0.48 V
Current at MPP, (I_{mp})	≈ 0.045 mA	≈ 0.060 mA
Maximum power, ($P_{max} = V_{mp} I_{mp}$)	≈ 0.020 mW	≈ 0.029 mW
Relative power increase	—	$\approx 45\%$ increase

5.1 Fill Factor

Fill Factor Calculation

Blue Curve (Lower / No Concentration)

- $V_{oc} \approx 0.55$ V
- $I_{sc} \approx 0.065$ mA
- $P_{max} \approx 0.020$ mW

$$FF_{blue} = \frac{0.020}{0.55 \times 0.065} = \frac{0.020}{0.03575} \approx 0.56$$

Orange Curve (Higher Concentration)

- $V_{oc} \approx 0.58$ V
- $I_{sc} \approx 0.085$ mA
- $P_{max} \approx 0.029$ mW

$$FF_{Org} = \frac{0.029}{0.58 \times 0.085} = \frac{0.029}{0.0493} \approx 0.59$$

The fill factor increases from approximately **0.56** to **0.59** under enhanced irradiance, indicating improved electrical quality of photovoltaic operation when coupled with the solar concentrator. This enhancement reflects a more pronounced, sharper knee in the I–V curve, suggesting reduced relative resistive losses and improved charge-carrier collection at higher photon flux.

From a mechanical and energy systems perspective, the modest increase in fill factor confirms that optical concentration improves power output without significantly degrading electrical performance, although the associated increase in thermal loading must be addressed to prevent long-term efficiency losses.

6. CONCLUSION

This research experimentally evaluated a low-concentration photovoltaic system using a Fresnel lens and a monocrystalline silicon solar cell to improve solar energy conversion while avoiding the complexity of high-concentration

systems. By adjusting the distance between the lens and the solar cell, rather than operating strictly at the focal point, the system achieved better electrical performance while reducing thermal stress. The results showed an increase in short-circuit current, a slight improvement in open-circuit voltage, and an overall power output enhancement of about 45% under concentrated sunlight. The fill factor also improved, indicating more efficient energy conversion. These findings demonstrate that low-concentration Fresnel-based photovoltaic systems offer a simple, cost-effective, and practical approach for enhancing solar energy output, making them suitable for sustainable and scalable renewable energy applications.

- **Findings:**

- The Fresnel lens caused a **~45% increase** in maximum power output (P_{max})
- The Fill Factor (FF) improved from **0.56 to 0.59**, indicating better electrical quality under concentration.
- The system is sensitive to focal distance; the study implies that adjusting the distance (defocusing) helps manage the trade-off between power gain and thermal damage.

To conclude, the proposed LCPV system offers an affordable and practical solution to improve solar energy conversion. Using lightweight PVC Fresnel lenses and precisely positioned focal points, notable efficiency gains are achievable without relying on complex or costly tracking systems. Future research should prioritize active cooling methods to maintain these

efficiency gains during prolonged operation.

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