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# Light Synergy: Solar Cell Output Optimization through Light Convergence Method (Integration of Convex Lens and Light Reflection)


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## ABSTRACT


This study experimentally examines how integrating a convex (Fresnel) lens and a reflector affects solar cell output performance, analyzing impacts of variations in lens distance, illuminance, and associated temperature changes. Experimental methodology involved testing various lens-to-cell distance configurations under both natural sunlight and artificial lighting. Results under direct sunlight demonstrate significant enhancement: a Fresnel lens positioned at an optimal 10 cm distance achieved a peak power output of 0.939 W, a 199.04% increase compared to baseline power (0.314 W) measured without optical components. Reflector use proved beneficial by redirecting unabsorbed light onto the solar cell's active surface and promoting more uniform distribution of concentrated light. This potentially reduces severe localized temperature gradients (hot spots), even as overall cell temperature increased due to high illuminance levels from light concentration, although specific temperature correlation analysis warrants further study. However, system effectiveness was negligible under tested artificial lighting conditions, highlighting a dependency on natural sunlight characteristics. These findings underscore potential for utilizing simple, cost-effective optical components to substantially optimize solar energy harvesting, particularly for applications in environments with consistent sunlight exposure, thereby advancing sustainable renewable energy solutions.



**Keywords:** Fresnel Lens, Reflector, Solar Cell Efficiency, Illuminance, Renewable Energy

## INTRODUCTION

Renewable energy has become a primary focus in global efforts to reduce dependence on fossil fuels and curb carbon emissions driving climate change. Among the various types of renewable energy, solar energy stands out due to its abundant availability and environmentally friendly nature. Solar cell technology, as the main device for utilizing solar energy, continues to evolve to enhance the efficiency of converting sunlight into electricity [1]. However, maximizing solar cell efficiency still faces significant challenges. Issues such as energy losses due to light reflection and scattering, material imperfections, and non-uniform illumination limit the optimal performance of solar cells. Furthermore, high solar cell surface temperatures are known to reduce energy conversion efficiency, particularly in concentrating photovoltaic (CPV) systems [2]. Under variable illumination conditions, the output power of solar cells often fails to reach its maximum potential, thereby hindering wider adoption. Although this study primarily focuses on optical enhancement through lenses and reflectors, the consequential impact on cell temperature due to light concentration is a critical consideration for overall system performance and durability [3].

In response to these challenges, various innovations have been developed. One promising approach involves the utilization of optical technologies to better manage incident sunlight. Convex lenses, for instance, can focus light, thereby increasing the intensity received by solar cell and potentially boosting output power [4]. Separately, light reflection techniques using reflective materials can redirect light that would otherwise be lost (e.g., light falling outside the cell area or reflected off its surface) back onto the active surface, thus increasing probability of energy absorption [5]. This research explores the concept of "Light Synergy," which, in this context, refers to the enhanced combined effect achieved through the strategic integration of a light-concentrating element (a convex Fresnel lens) with a light-redirecting element (a reflector). The lens focuses incident sunlight onto the solar cell to increase intensity, while the reflector captures stray, reflected, or peripheral light and redirects it back onto the cell's active area. This synergy aims to maximize photon capture and improve light uniformity across the cell surface, potentially mitigating issues such as hot spots while enhancing power output beyond what either component could achieve individually [6].

Previous studies have demonstrated the potential of individual optical components. Systems employing Fresnel lenses, have shown success in increasing Illuminance and conversion efficiency [7]. However, many applications focus on large-scale and complex CPV systems, whereas investigations into simpler, integrated approaches combining lenses and reflectors for standard flat-plate solar cells, particularly under varying conditions, remain less common. Furthermore, although the impact of temperature on solar cell efficiency is acknowledged, research often focuses on material solutions or complex active cooling systems rather than optimizing optical configurations to potentially improve thermal distribution concurrently with power output [2]. Therefore, a research gap exists in comprehensively evaluating the synergistic integration of simple convex lenses and reflectors as a practical and potentially cost-effective method to enhance solar cell power output under diverse conditions.

To address this gap and contribute new insights, this research aims to explore and evaluate the potential of integrating optical technologies (specifically convex lenses and light reflection techniques) to increase the output power of solar cells. Specifically, this research focuses on: 1) Analyzing the effect of using convex lenses on increasing the Illuminance received by solar cells and its impact on output power efficiency; 2) Evaluating the contribution of light reflection techniques in redirecting unabsorbed light to the active surface of the solar cell to increase energy absorption; 3) Testing the effectiveness of the synergistic integration of convex lenses and light reflection under various lighting conditions (natural sunlight vs. artificial light) to assess its viability for practical and economical optimization of solar cell performance.

Although temperature is a known factor influencing efficiency and will be monitored, the primary independent variables manipulated and analyzed are the optical components and their configuration (lens distance) under different light sources. The goal is to develop insights into a light synergy model that can support the development of more efficient solar cell applications and contribute to sustainable renewable energy solutions. The urgency of this research lies in its potential to enhance renewable energy efficiency, particularly solar technology, which is a crucial component in global decarbonization efforts. Amid concerns about energy security and increasing environmental awareness, this work offers an innovative yet potentially simple approach to maximizing solar cell power output. Theoretically, this research is expected to advance scientific understanding in the field of solar energy, especially regarding the mechanism of light synergy through the integration of convex lenses and reflectors.

## RESEARCH METHOD

This research is conducted using an experimental approach. The method that will be used to achieve the goal of solar cell output power optimization through the integration of convex lens and reflector tools consists of several main stages detailed in the following research flow chart in figure 1.

This research employs an experimental approach to investigate the enhancement of solar cell power output through the synergistic integration of a convex lens and a reflector. The methodology followed a structured procedure, commencing with a literature review to synthesize current information on integrating optical components with solar cells and analyze previous studies on convex lens effects. This informed the subsequent detailed experimental planning and design, preliminary testing, data analysis, and validation under varied operational conditions.

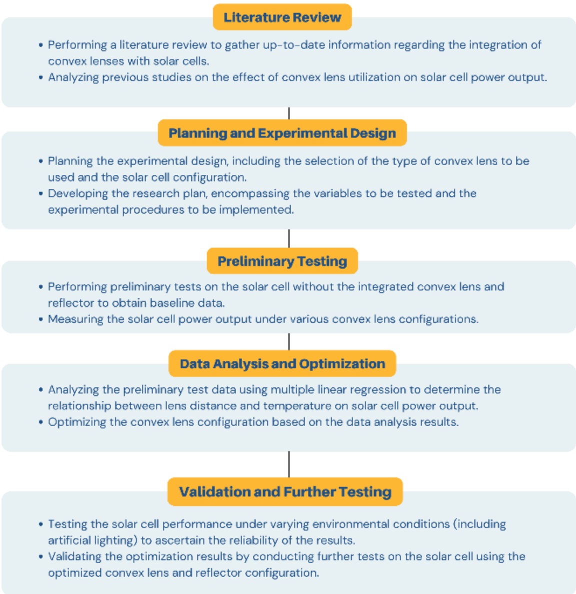



**Figure 1.** Research flowchart

The core of the experiment involved evaluating the "light synergy" achieved by combining a light-concentrating element (Fresnel lens) with a light-redirecting element (reflector). Specifically, a convex Fresnel lens focused incident light onto the solar cell's active surface to increase Illuminance. Concurrently, an angle-adjustable planar reflector, constructed from aluminum foil with its shiny, more specular surface facing the cell, was positioned adjacent to the solar cell. Its function was to capture and redirect unabsorbed or stray photons (such as light initially missing the cell or reflected from its surface) back towards the active area. This combined action aimed to maximize photon capture and enhance overall power output compared to the baseline (unassisted) solar cell.

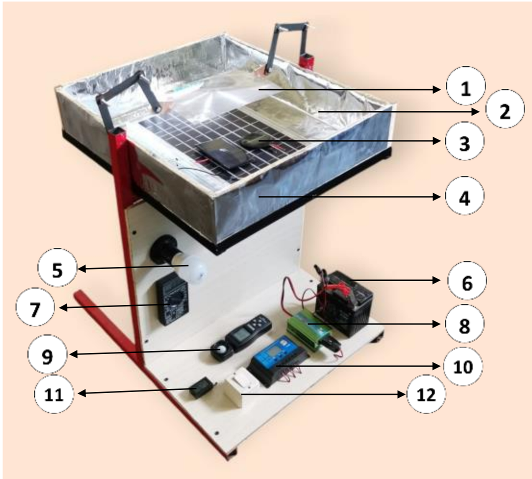



**Figure 2** Experimental prototype

Figure 2. displays the constructed experimental prototype utilized for this research. The primary photovoltaic (PV) assembly, located at the top, features the solar panel (5 volt monocrystalline silicon) (3), which converts incident solar radiation into direct current (DC) electricity. This panel is held in place by a dedicated mounting structure (4) designed for stability and optimal solar exposure. Positioned above the panel are the optical enhancement components: a Fresnel lens (3x magnification, 15x20) (1), intended to concentrate sunlight and increase the Illuminance on the solar panel, and a reflector (2), strategically placed to redirect additional sunlight onto the panel's active surface.

The base of the prototype houses the electrical management, storage, and instrumentation components. This includes a solar charge controller (10) for regulating battery charging and protecting the battery (6) from overcharge or deep discharge. The battery (6) serves as the energy storage unit. An inverter (8) is present for potential conversion of DC energy to AC, with a light bulb (5) connected as a representative load. Instrumentation comprises a digital multimeter (7) for measuring electrical parameters, a lux meter (9) for quantifying incident Illuminance, and a digital thermometer (11) for monitoring the solar panel's temperature. A main switch (12) allows for manual control of the electrical circuit. This integrated prototype facilitated the experimental investigation of the optical components' impact on the system's overall performance under real-world and controlled conditions.

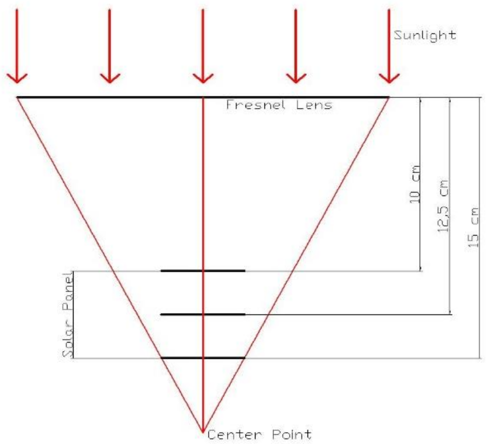



**Figure 3.** Determining the distance of the lens to the panel surface

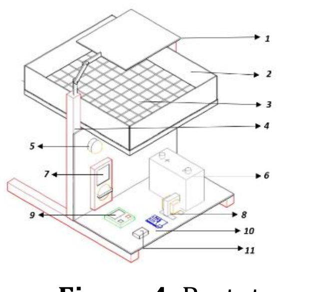
Figure 3. illustrates the optical principle of the Fresnel lens employed as the light-concentrating element in this experiment. Akin to a conventional convex lens, the Fresnel lens utilizes a series of precisely angled concentric annular sections (prisms or grooves) etched onto a thin substrate. These sections collectively refract incident parallel sunlight, converging the rays towards a common focal point (Center Point), as shown by the red lines representing the light path. This convergence significantly increases the solar Illuminance (Illuminance per unit area) on a surface placed near the focal plane. As depicted, the experimental setup involved positioning the solar panel at varying lens-to-cell distances (10 cm, 12.5 cm, and 15 cm) relative to the lens. This variation allowed for the systematic evaluation of system performance as the solar cell's active surface intersected different regions of the converging light beam, encompassing positions potentially near, at, or slightly beyond the optimal focal distance, thereby investigating the impact of focus quality and light concentration levels.

The experimental procedure encompassed several key stages. Initially, baseline performance data were established by testing the solar cell without the Fresnel lens and reflector under direct natural sunlight. These tests were conducted in Palangkaraya, Central Kalimantan, Indonesia during mid-day hours (10:00 AM - 2:00 PM local time) on November 13, 2024, under predominantly clear sky conditions, with ambient outdoor temperatures ranging from 35°C to 47°C. Subsequently, the solar cell's output was measured with the integrated Fresnel lens and reflector system configured at varying lens-to-cell distances (10 cm, 12.5 cm, 15 cm), primarily under direct natural sunlight. During all tests, key parameters were measured using appropriate instrumentation: Illuminance *(Illuminance)* was measured using a lux meter, solar cell surface temperature (°C) was monitored using a digital thermometer, and the electrical output was characterized by measuring voltage (V) and current (A) with a digital multimeter. The power output (P) was then calculated from the measured voltage and current using Equation (1):

$$\boldsymbol{P} = \boldsymbol{V} \times \boldsymbol{I}$$

Where P represents the power output in Watts (W), V is the voltage in Volts (V), and I is the current in Amperes (A). Systematic recording of these variables was performed for each configuration and condition, as illustrated in the data collection process (Figure 5).

Finally, validation tests were conducted under different environmental conditions, specifically using artificial lighting provided by a 20 W LED lamp with a rated luminous flux of 2100 lumens. The LED lamp was positioned at a fixed distance of 50 cm directly above the Fresnel lens. This distance was selected experimentally, as preliminary adjustments indicated that positioning the lamp closer or farther than 50 cm resulted in less effective capture of the inherently diffuse LED light by the Fresnel lens; the 50 cm distance provided the most optimal alignment to subsequently achieve the targeted measured intensities on the solar cell surface. Utilizing LEDs for solar simulation is well-documented, emphasizing their advantages such as cost-effectiveness, low power consumption, and long lifespan, which make them ideal candidates for controlled testing environments in photovoltaic research [8]. This setup allowed for the assessment of the system's effectiveness and consistency beyond natural sunlight. Performance with the optical components was compared against the baseline under these controlled conditions as well. The experimental variables investigated included the lens-to-cell distance, Illuminance source (natural vs. artificial), and the resultant solar cell temperature, with the primary outcome measure being the electrical power output. Data analysis focused on comparing the performance between the baseline and the integrated optical system configurations. Furthermore, it is recognized that the effectiveness of LED-based solar simulators is associated with their ability to produce a reliable and consistent light spectrum, which can be tailored for optimal photovoltaic performance[9][10].




| No. | Part Name |
|---|---|
| 1 | *Fresnel Lens* |
| 2 | *Reflektor* |
| 3 | *Solar Panel* |
| 4 | *Solar Panel Mounting Structure* |
| 5 | *Light Bulb* |
| 6 | *Battery* |
| 7 | *Digital Avometer* |
| 8 | *Travo (Inverter)* |
| 9 | *Thermometer Digital* |
| 10 | *Solar Charge Controller* |
| 11 | *Switch* |

**Figure 4.** Prototype design plan

## RESULT AND DISCUSSION

### Initial Testing Results

Initial tests were conducted to evaluate the effects of integrating fresnel lens and light reflection on increasing light absorption by solar cells.


**Figure 5.** Data collection

Figure 5. Collage illustrating key steps in the experimental procedure and data collection process: (1) Measurement and adjustment of the distance between the Fresnel lens and the solar cell. (2) Positioning of the experimental setup under direct natural sunlight for testing. (3) Measurement of voltage (V) and current (A) output from the solar cell using a digital multimeter. (4) Measurement of incident Illuminance.

At this stage, the optical system is tested with various parameters, such as lens distance, reflector mounting, temperature and Illuminance in table 1 and 2.

The results show that positioning the convex lens at an optimal distance ranging from 10-15 cm from the solar cell enhances electrical output. Within this distance range, light can be optimally focused, enabling its more efficient absorption within the solar cell. Research by Costa et al. illustrates how different concentrator configurations, including Fresnel lenses, impact photovoltaic system performance, providing a strong rationale for the observed enhancement [11]. Furthermore, the correlation between optimal power output and lens focusing distance has been demonstrated by Asrori et al., although their study focused specifically on water heating applications employing Fresnel lenses [12].

**Table 1.** Initial test result data without using fresnel lens and reflector

| Illuminance (Lux) | Temperature (°C) | Voltage (Volt) | Current (Ampere) | Solar Cell Output (W) |
|---|---|---|---|---|
| 180,500 | 46 | 6.28 | 0.05 | 0.314 |

**Table 2.** Initial test result data using fresnel lenses and reflectors

| Lens Distance (cm) | Illuminance (Lux) | Temperature (oC) | Voltage (Volt) | Current (Ampere) | Solar Cell Output (W) |
|---|---|---|---|---|---|
| **10** | Error | 60 | 6.26 | 0.15 | 0.939 |
| **12.5** | Error | 68 | 6.32 | 0.12 | 0.758 |
| **15** | Error | 75 | 6.69 | 0.12 | 0.803 |

With respect to the measurement instrumentation, readings indicating an 'Error' status for Illuminance signify that the upper measurement limit of the employed lux meter was exceeded, consistent with the conclusion drawn by Brągoszewska et al. stating that specific measurement instruments have limitations in capturing high intensities [13]. As the Illuminance significantly surpassed the 200,000 lux threshold, this phenomenon does not represent a measurement failure but rather demonstrates the effectiveness of the Fresnel lens concentration technology, capable of generating a very high photon flux density

[14]. The temperature variation from 60°C to 75°C shows an increase in the Illuminance received by the solar cell at different lens distances, which contributes to an increase in the light-to-electricity conversion efficiency.

The management of temperature in photovoltaic systems is crucial for maintaining energy conversion efficiency, particularly in concentrated photovoltaic (CPV) systems, where high temperatures can adversely affect current output due to excessive Illuminance. Elevated temperatures can enhance the efficiency of solar panels up to a certain threshold; beyond that, the effects can be detrimental. Insufficient thermal management in CPV systems can lead to significant performance losses as temperature rises [15]. The use of Fresnel lenses plays a pivotal role in optimizing temperature distribution across solar cells, thereby mitigating the development of hot spots that can result in localized overheating [16][17].

Effective thermal management strategies in CPV systems are essential to counteract the thermal stresses imposed by high concentration ratios. Proactive designs incorporating features such as heat sinks and cooling technologies are recommended [15]. Moreover, innovative Fresnel lens designs that improve light distribution are currently under investigation, with findings suggesting that better Illuminance distribution correlates with improved thermal performance and efficiency of photovoltaic systems [18][19]. Thus, integrated approaches addressing both concentration and thermal management are vital for optimizing the performance of solar energy technologies under varying Illuminance conditions.

The addition of reflectors to solar cells has been shown to improve the utilization of incident light by redirecting stray photons and potentially enhancing the uniformity of illumination across the cell's active area compared to a sharply focused beam from the lens alone. Reflectors can significantly enhance output efficiency by ensuring a more uniform distribution of light, which is essential in optimizing the performance of photovoltaic systems. This phenomenon is particularly evident as reflectors can mitigate the impact of non-uniform Illuminance by redirecting light towards the active areas of solar panels, thereby increasing overall power generation [20] and while work by [21] highlights benefits in reducing shadow interference. While light concentration inherently leads to increased cell temperatures, as observed in this study (Table 2), reflectors may play a role in mitigating highly localized temperature peaks (hot spots) by homogenizing the distribution of the concentrated thermal load. This improved thermal distribution, rather than a reduction in overall temperature, could contribute to better long-term cell performance and durability, although a detailed thermal mapping was beyond the scope of this initial investigation. Overall, reflectors contribute to maximizing light capture and promoting a more uniform energy flux distribution on the cell surface.

The experimental results demonstrate a distinct correlation between the convex lens distance and the solar cell power output. Specifically, the power output reached a maximum of 0.939 W at a lens distance of 10 cm. This output subsequently decreased to 0.758 W at 12.5 cm, followed by an increase to 0.803 W at 15 cm. These variations suggest that an optimal lens distance is critical for maximizing light concentration, thereby significantly impacting the solar cell's power output. Consistent with these findings, [12] reported that adjusting the Fresnel lens distance is fundamental to enhancing light concentration and augmenting power output from solar applications. Furthermore, [22] emphasized that employing optical devices, such as Fresnel lenses, is pivotal for refining solar energy collection and overall system performance. Collectively, these findings underscore that precise adjustments in lens positioning are vital not only for optimizing solar energy capture but also for achieving maximum efficiency in solar energy systems. This aligns with the principles concerning Fresnel lens applications discussed by [14][23].

Operational conditions such as distance and Illuminance must be optimized to avoid adverse effects, such as current degradation due to high temperatures. Optical system optimization is crucial. Lenses and reflectors should be configured not only to maximize incident Illuminance but also to manage the resulting thermal load by promoting a reasonably uniform distribution of concentrated light, thereby balancing power enhancement against potential temperature-induced degradation effects. A solar cell's power output is critically influenced by both the spectral distribution of incident light and the uniformity of illumination across its surface. Consequently, mismatches between the spectrum of the focused light and the cell's spectral response, coupled with non-uniform light distribution, can lead to a significant reduction in power conversion efficiency and electrical performance.

These detrimental effects are particularly pronounced in concentrator photovoltaic (CPV) systems and multi-junction solar cells [24][25] added that temperature management is very important because the accumulation of thermal energy can reduce the energy conversion efficiency of solar cells [26], also highlighted that optical system design should consider changes in lighting conditions and incident angles to maintain efficiency. Overall, proper lens spacing and reflector design are essential to maintain stable temperature and light distribution, thereby preventing current degradation and improving solar cell energy conversion efficiency.

**Analysis and Optimization**

An analysis of the experimental data reveals the interplay between the primary independent variable, lens distance, the resulting cell temperature, and the solar cell's power output. The relationship between these factors dictates the system's overall performance. Initial observations from the collected data (presented in Table 2 and

Figures 6 & 7) provide insights into these interactions.

Based on preliminary observations from the available data, at a distance of 10 cm and a temperature of 60°C, the power output was 0.939 W. When the distance increased to 12.5 cm and the temperature reached 68°C, the power output dropped to 0.758 W. However, at a distance of 15 cm and a temperature of 75°C, the power output increased slightly to 0.803 W. These observations show a non-monotonic relationship between lens distance and power output within the tested range, initially decreasing and then slightly increasing. Concurrently, higher cell temperatures, resulting from increased light concentration or variations in focusing, appear generally correlated with changes in power output, likely influenced by the known negative temperature coefficient of photovoltaic cells and the complexities of heat dissipation under concentrated Illuminance.

Further analysis required to comprehend the power output fluctuations from systems employing Fresnel lenses can be contextualized through detailed studies on the performance of photovoltaic (PV) panels integrated with solar concentration systems. The measurements indicate power fluctuations, exhibiting a maximum output of 0.939 W at a distance of 10 cm, followed by a decrease to 0.758 W at 12.5 cm. This reduction can be attributed to the concept of optimal focal distance, often a critical factor in PV concentrator systems. Non-ideal concentration systems can impair the Illuminance distribution, thereby diminishing the power efficiency of PV panels [15]. Research indicates that elevated panel temperatures (in this instance, from 60 °C to 68 °C) negatively correlate with photovoltaic cell efficiency, which typically declines as temperature increases [27]. This behavior aligns with observations that higher temperatures lead to a reduction in solar-to-electrical conversion efficiency [28].

Intriguingly, the power output recovered slightly at 15 cm, despite a further temperature increase. This suggests a complex interplay in the focused light distribution, potentially involving a balance between intensity and uniformity reaching the panel [29], or specific characteristics of the Fresnel lens configuration [30]. Nevertheless, it is crucial to reiterate that despite this minor upturn at 15 cm, the 10 cm distance provided the definitive maximum power output, confirming it as the optimal focal distance in this experimental setup. Furthermore, it is well-documented that excessive concentration or improper focusing can induce localized hot spots, posing a risk of irreversible damage to PV materials [28].

The decision to terminate the experiment at the 15 cm distance is substantiated by this evidence, underscoring the importance of considering operational limits to maintain photovoltaic panel integrity during experimentation [15]. Although the peak output was measured at 10 cm, regression analysis provides a necessary model for predicting system behavior within this established safe operating range and reinforces the need for cautious extrapolation beyond potentially damaging thresholds [31]. Therefore, the power recovery observed at 15 cm should not be interpreted as indicative of potential further gains at greater distances but rather as a consequence of the unique equilibrium between thermal and optical factors occurring at that specific distance [15].

The following graph displays the relationship between variations in lens distance, temperature and the increase in solar cell output:

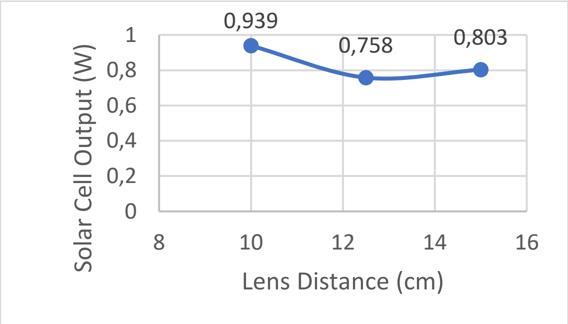



**Figure 6.** Graph of the relationship between lens distance and solar cell output

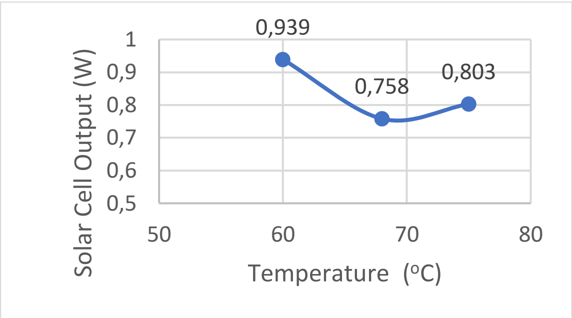



**Figure 7.** Graph of temperature relationship to solar cell output

Positioning the lens closer to a solar cell surface can increase focused light intensity, yet this introduces an over-focusing risk, potentially causing overheating and reduced efficiency. The orientation and tilt of photovoltaic (PV) panels significantly influence solar Illuminance capture and electrical energy yield, although their work did not specifically address lens distance or reflector spacing. [32] highlighted the significance of inter-reflector angles and spacing for achieving uniform light distribution, noting that reflectors positioned too closely can induce overheating and potentially damage the solar cells [33]. A comprehensive analysis by [34] indicated that performance losses in photovoltaic systems are influenced by thermal effects, yet it did not specifically confirm a direct correlation between optimal spacing configurations and enhanced efficiency. Furthermore, [35][36] emphasized the importance of solar tracking systems for adapting to varying sunlight conditions, thereby enhancing energy output and preventing potential solar cell damage. Consequently, meticulous adjustment of reflectors and the implementation of dynamic systems are necessary to maximize power output without compromising efficiency due to excessive thermal buildup.

**Validation and Advanced Testing**

Validation is conducted to ensure that the optimal configuration that has been found can be applied consistently under different environmental conditions. At this stage, tests were conducted under natural lighting conditions (direct sunlight) and compared to indoor tests with artificial lighting.

The subsequent validation tests conducted under artificial illumination yielded a consistent power output of zero watts (0 W) across all evaluated lens-to-cell distances (10 cm, 12.5 cm, and 15 cm), as detailed in Table 5. This result persisted despite measurable increases in the incident Illuminance, ranging from 3269 Lux to 3763 Lux, and the presence of a non-negligible open-circuit voltage (Voc) between 4.24 V and 4.49 V. The primary underlying cause for this null power generation is attributed to a fundamental spectral mismatch between the emission spectrum of the employed artificial light source and the spectral response characteristics of the photovoltaic cell. Silicon-based solar cells are predominantly optimized for the broad spectral distribution of natural sunlight (approximated by the AM1.5G spectrum), which contains a high flux of photons with energies exceeding the silicon bandgap (~1.1 eV). Artificial light sources, conversely, often exhibit significantly narrower or spectrally distinct emission profiles.

**Table 3.** Advanced test data with artificial light

| Lens Distance (cm) | Illuminance (Lux) | Voltage (Volt) | Current (Ampere) | Solar Cell Output (W) |
|---|---|---|---|---|
| 10 | 3269 | 4.24 | 0.00 | 0.000 |
| 12.5 | 3446 | 4.45 | 0.00 | 0.000 |
| 15 | 3763 | 4.49 | 0.00 | 0.000 |

Consequently, it is highly probable that a substantial portion of the photons emitted by the artificial source possessed energies below the required bandgap threshold, rendering them incapable of generating electron-hole pairs. While the Fresnel lens effectively concentrated the incident radiation, as evidenced by the increased Lux values, it inherently focuses the impinging spectrum without altering its constituent wavelengths.

Therefore, it primarily amplified the intensity of photovoltically ineffective radiation on the cell surface. The measured Voc indicates that the cell was photosensitive and some potential difference was established. However, the generation rate of usable charge carriers was insufficient to overcome intrinsic recombination losses and system resistance, resulting in a negligible short-circuit current (Isc ≈ 0 A). Since electrical power output is the product of voltage and current ($P = V \times I$), the absence of a significant current inevitably leads to zero power generation. This finding unequivocally highlights the system's critical dependence on the spectral quality of the illumination source and elucidates its ineffectiveness under the specific artificial lighting conditions tested, contrasting sharply with its performance enhancement observed under natural sunlight.

**Table 4.** Data on validation results and further testing

| Lighting Condition | ***Output Without Lens* (W)** | ***Output with Lens and Reflector* (W)** | **Percentage Increase** |
|---|---|---|---|
| Direct Sunlight | 0.314 | 0.939 | 199.04% |
| Artificial Lighting (3269 Lux) | 0 | 0 | 0 |

Based on the validation results and further testing in the table above, it can be seen that the optimal configuration with convex lenses and reflectors provides significant results in increasing the output of solar cells, especially in natural lighting conditions such as direct sunlight. Under direct sunlight conditions, the output without the lens is 0.314 W, while with the lens and reflector it increases to 0.939 W, giving an increase of 199.04%. This shows that the integration of convex lenses and reflectors is effective in converting sunlight into greater electrical energy.

However, under artificial lighting conditions, both the output without lens and with lens and reflector recorded 0 W, so no improvement could be observed. This result indicates that this light convergence system may lack responsiveness or be unable to optimize artificial lighting at certain intensity levels. Factors such as incident light angle, lighting intensity, and the efficiency of the reflector in capturing and focusing artificial light need to be further investigated.

Overall, this data supports the effectiveness of using convex lenses and reflectors to increase solar cell output under direct sunlight conditions. However, applications in artificial lighting conditions still require further adjustments or optimization for this technology to work well in various environments.

## CONCLUSION

Based on the experimental results, it can be concluded that the light convergence method, through the integration of a Fresnel (convex) lens and a reflector, significantly enhances the power output of solar cells. An optimal lens-to-cell distance configuration of approximately 10 cm was found to produce a more uniform and efficient Illuminance on the solar cell surface, resulting in a peak power output of 0.939 W. This represents a 199.04% increase compared to the baseline power of 0.314 W measured for the solar cell without optical components under direct sunlight. The use of a reflector also proved effective in distributing light more uniformly and capturing potentially lost photons, thereby improving the solar cell's energy conversion capability.

However, it is important to note that the system exhibited negligible effectiveness under the tested artificial lighting conditions, yielding 0 W of power output across all configurations despite measurable incident Illuminance (ranging from 3269 Lux to 3763 Lux). This was attributed to a fundamental spectral mismatch between the emission spectrum of the artificial light source and the spectral response characteristics of the solar cell. These findings highlight the potential of this method as a simple and cost-effective solution for enhancing solar energy harvesting efficiency, particularly for applications in environments with consistent and abundant natural sunlight exposure, such as small-scale solar power systems or off-grid applications.

Recommendations for future research include:

1. A more detailed thermal investigation to accurately map the temperature distribution on the solar cell surface, identify potential hot spot formation due

to light concentration, and explore simple passive cooling strategies.

2. Testing the system's effectiveness using various types of solar cells (e.g., monocrystalline, polycrystalline, or other types) and variations in Fresnel lens design and material (e.g., with different focal lengths) to explore more optimal configurations.
3. A long-term study on the durability and degradation of the optical components (lens and reflector) and the solar cell itself under operational conditions with concentrated light.

Further research in this area is expected to refine the design and application of light convergence technology for more efficient and sustainable renewable energy solutions.

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