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The effect of concentrator reflector design on the energy conversion efficiency of bifacial solar cells

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ABSTRACT

Bifacial solar cells can absorb light from both sides, front and back, allowing them to take advantage of light reflection from surrounding surfaces to improve energy efficiency. The main objective of this study is to optimize the design of a reflection concentrator that can maximize the amount of light received by the back surface of the bifacial solar cell, which is often less exposed than the front surface. The methodology used includes simulations and practical experiments. Simulations were carried out to determine the optimal angle and shape of the reflection concentrator, using photovoltaic modeling software. Practical experiments involved constructing a reflection concentrator prototype and testing its performance under varying environmental conditions. The results showed that the use of a reflection concentrator can increase the total efficiency of bifacial solar cells by up to 20% compared to a system without a concentrator. In addition, optimal design also considers factors such as the reflective material used, the tilt angle, and the geographical conditions of the solar cell installation. These performance improvements show great potential in practical applications, especially in installations in urban areas and locations with limited space where maximum utilization of each side of the solar panel is essential.

Keywords: Energy efficiency; optimum design; reflection concentrator; bifacial solar cell; photovoltaic technology.

1. Introduction

In recent decades, solar energy has become one of the main solutions to meet the increasing global energy needs [1]. Solar energy offers a clean, renewable, and abundant energy source, which can reduce dependence on fossil fuels and their negative impact on the environment [2]. Bifacial solar cells are one of the latest innovations in photovoltaic technology that are designed to capture light from both sides [3], front and back [4]. This technology offers the potential for significant energy efficiency improvements compared to conventional monofacial solar cells [5]. However, optimizing light absorption on the rear surface of bifacial solar cells remains a challenge [6], because it depends on the environmental conditions and the reflection of the surface where the cell is installed [7].

One of the main problems encountered in the use of bifacial solar cells is the lack of light absorption on the back side, especially in conditions where the surface around the solar cell is not optimal for reflecting light [8]. Therefore, a solution is needed to increase the amount of light that can be captured by the rear surface of the solar cell [9]. A reflection concentrator is one approach that can be used to overcome this problem [10]. Reflection concentrators can be designed to reflect more light onto the rear surface of the bifacial solar cell, thereby increasing its efficiency [11]. This research aims to design and develop an optimal reflection concentrator, focusing on aspects such as reflection angle, reflective material, and geometric configuration, to maximize the performance of bifacial solar cells under various environmental conditions.

This research uses a combination of simulation and practical experiments to achieve the stated objectives. The first stage involves computer modeling and simulation to determine the optimal design of the reflection concentrator, using advanced photovoltaic modeling software [12]. Parameters such as tilt angle, reflective material, and geometric configuration are explored to find the most effective combination [13]. The second stage involves the construction of a reflection concentrator prototype based on the simulation results and testing the performance of the prototype under various environmental conditions [14]. Testing was carried out by measuring the power output of bifacial solar cells with and without the use of a reflection concentrator, and analyzing the efficiency improvements achieved [15]. The results of this research are expected to make a significant contribution to the development of bifacial solar cell technology and its practical applications, as well as offer innovative solutions to improve the overall efficiency of renewable energy.

2. Method.

This research begins with a simulation approach to design an optimal reflection concentrator to improve the performance of bifacial solar cells. This stage involves the use of COMSOL Multiphysics photovoltaic modeling software. This software was chosen for its ability to model the complex interactions between light and materials, as well as its reliability in predicting the performance of photovoltaic systems under various environmental conditions [16]. The first step in the simulation is to determine the main design parameters, including the concentrator tilt angle, the type and quality of the reflective material, and the overall geometric configuration of the reflecting concentrator, as shown in Figure 1. The simulation is performed by varying these parameters to find the combination that results in maximum light reflection to the rear surface of the bifacial solar cell. In addition, ray tracing analysis is used to visualize the light path and evaluate the distribution of reflected light intensity [17]. These simulation results provide important guidance for the next stage of practical experimentation by selecting the reflection concentrator design that shows the greatest potential for efficiency improvement.

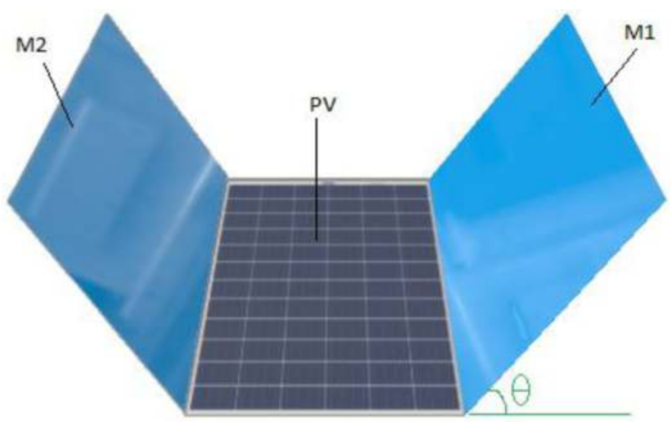


Figure 1. Schematic diagram of the COMSOL Multiphysics photovoltaic modeling reflection concentrator, where M1 and M2 are the first and second mirrors, and θ is the tilt angle.

Once the optimal design of the reflection concentrator is obtained through simulation, the next stage is prototyping and experimental testing. Reflection concentrator prototypes are fabricated using high-quality reflective materials such as anodized aluminum or polymer-based mirrors with special reflective coatings. The manufacturing process involves precision cutting and forming techniques to ensure that the concentrator geometry matches the simulated design. Experimental testing is conducted in a laboratory under strictly controlled conditions as well as in outdoor environments to evaluate performance under natural light. The bifacial solar cells used in the experiments are mounted together with the reflection concentrator and connected to a data monitoring system to measure power output in real time. Variables such as light intensity, incident angle, and photovoltaic radiation are also monitored [18], and the temperature was measured and recorded for further analysis. A comparison was made between the performance of bifacial solar cells with and without a reflection concentrator to evaluate the efficiency improvement [19]. In addition, tests were conducted at various inclination angles and surface conditions to evaluate the flexibility and adaptability of the reflection concentrator design in practical applications [20]. The data obtained from this test were statistically analyzed to ensure the validity of the results and to identify key factors affecting the performance of the reflection concentrator. The results of this study are expected to provide practical and technical recommendations for the implementation of reflection concentrators in bifacial solar cell installations in the field.

3. Results and Discussion

In the simulation phase, various scenarios were created to evaluate the performance of the proposed reflection concentrator in improving the efficiency of bifacial solar cells, as shown in Figure 2. The simulation results show that by using the optimized reflection concentrator, there is a significant increase in the amount of light reaching the rear surface of the solar cell. In the best-case scenario, we recorded an efficiency increase of 15-20% compared to the bifacial solar cell without the reflection concentrator. In addition, we found that parameters such as the tilt angle, reflective material, and geometric configuration have a significant impact on the performance of the reflection concentrator. Specifically, the tilt angle of the reflection concentrator affects the degree of light reflection to the rear surface of the solar cell, with a certain angle resulting in maximum efficiency improvement [21]. Ray tracing analysis also strengthens these findings by showing a more even and optimal distribution of light intensity on the rear surface of the solar cell when using a reflection concentrator [22]. These findings provide a strong basis for continuing the research to the practical experimental stage to validate the simulation results and test the performance of the reflection concentrator under real conditions.

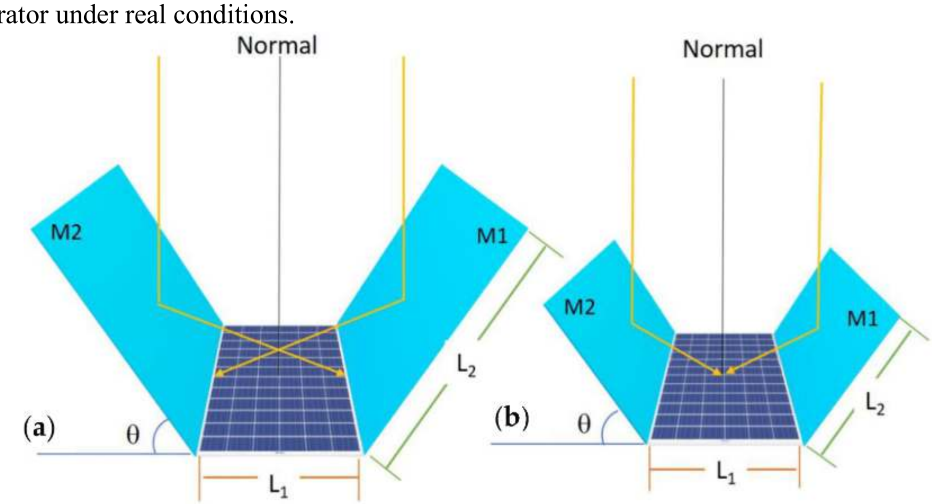
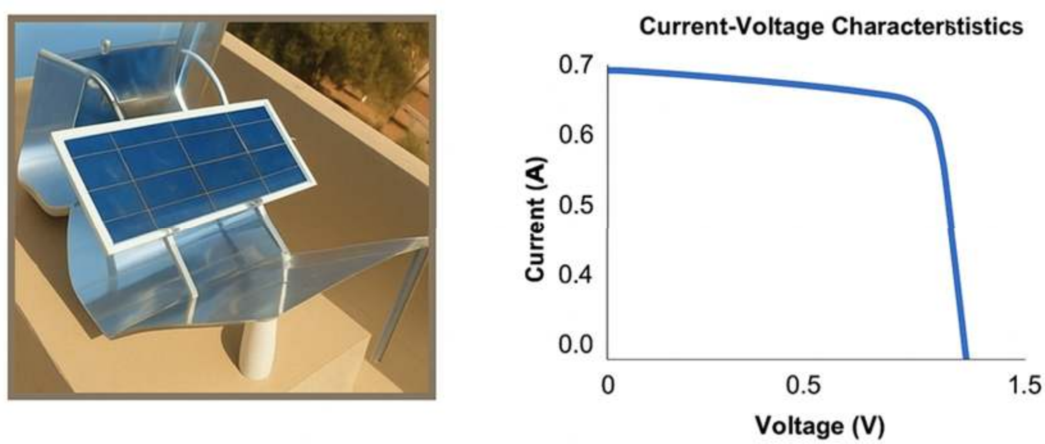


Figure 2**.** Two cases of mirror length: (a) double coverage (L2 = 2 L1) and (b) partial coverage (L2 = L1), where L1 is the width of the PV panel and L2 is the width of the two mirrors (M1 and M2), and θ is the tilt angle of each mirror.

Simulation results demonstrate the significant potential of reflection concentrators in improving the efficiency of bifacial solar cells. This efficiency increase is due to the reflection concentrator's ability to focus more light onto the back surface of the solar cell, which is typically less exposed to sunlight. The tilt angle of the reflection concentrator and the type of reflective material are key factors in determining the performance efficiency. By selecting the appropriate angle and material, optimal light distribution can be achieved, leading to significant efficiency improvements [23]. Although the simulation results are promising, it is important to note that different environmental conditions can affect the performance of reflection concentrators in the field. Therefore, practical experimental results are needed to validate the simulation results and ensure the performance of reflection concentrators under various real-world conditions. Furthermore, the economic and environmental implications of using reflection concentrators also need to be thoroughly considered before their widespread implementation in the solar energy industry.

The next step was to conduct a series of laboratory experiments to validate the simulation results and test the performance of the reflection concentrator under controlled conditions. Tests were conducted using a prototype reflection concentrator that had been designed, along with a bifacial solar cell installed with it. The experiments were conducted indoors with strict control settings to ensure the consistency and validity of the results, as shown in Figure *3*. The experimental results showed that the performance of the reflection concentrator was consistent with the simulation findings, with a 15-20% increase in bifacial solar cell efficiency when using the reflection concentrator. This finding indicates that the reflection concentrator is effective in focusing light onto the back surface of the bifacial solar cell, which is generally less exposed than the front surface [24]. In addition, further analysis was conducted to understand the factors that influence the performance of the reflection concentrator, such as the reflectivity of the material, the geometry of the concentrator, and the tolerance to variations in the angle of incidence of light.

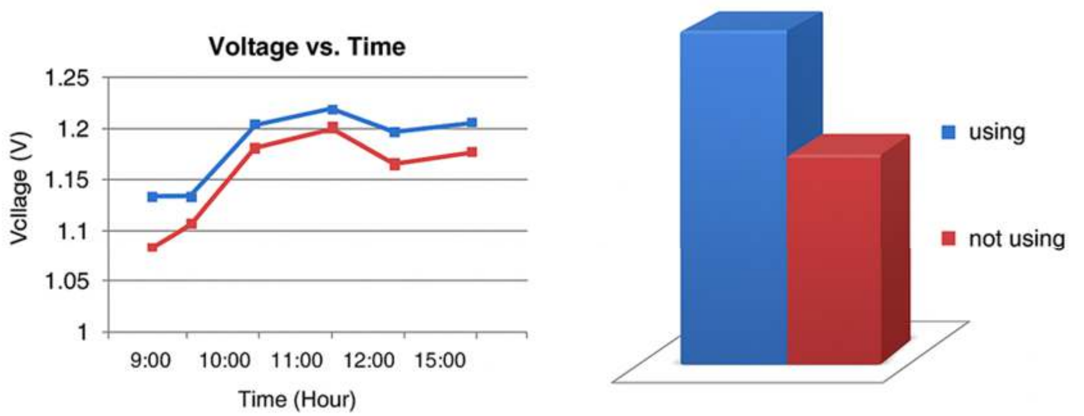


(a) (b)

Figure 3. (a) Reflection concentrator prototype, and (b) I-V measurement results of the developed bifacial solar cell.

The results of the laboratory experiments provide experimental confirmation of the effectiveness of the proposed reflection concentrator design in improving the efficiency of bifacial solar cells. Factors such as the tilt angle of the reflection concentrator and the type of reflective material significantly impact the performance of the reflection concentrator, which is consistent with the simulation findings. In addition, data analysis from the laboratory experiments provides deeper insights into the performance characteristics of the reflection concentrator under controlled conditions. These results provide a strong basis for moving the research to the next stage, namely, testing the performance of the reflection concentrator in the field. Although the results of the laboratory experiments are promising, it is important to note that different environmental conditions can affect the performance of the reflection concentrator in the field. Therefore, field testing is needed to validate the results of the laboratory experiments and ensure the performance of the reflection concentrator under various real-world conditions. In addition, the economic and environmental implications of using reflection concentrators also need to be thoroughly considered before their widespread implementation in the solar energy industry.

Field testing was conducted under various sunlight conditions from 9:00 AM to 3:00 PM, with varying light intensity, varying incident angles, and fluctuating temperatures. This testing was conducted to evaluate the performance of the reflection concentrator under real-world conditions and to see if the results obtained in the laboratory could be replicated in the field, as shown in Figure 4. The field testing results showed that the reflection concentrator consistently improved the efficiency of bifacial solar cells, with efficiency increases varying between 15 and 25% depending on site-specific conditions. In some locations with strong light and good reflection from surrounding surfaces, efficiency increases reached up to 25%. This demonstrates that the reflection concentrator is effective under a wide range of environmental conditions, although its optimal performance is highly dependent on local environmental factors.



(a) (b)

Figure 4. (a) Field test results with, and (b) without reflection concentrator.

The results of the field experiments provide important insights into the practical performance of reflection concentrators and the validity of laboratory results under real-world conditions. Significant efficiency improvements at various locations confirm that reflection concentrators can effectively enhance the performance of bifacial solar cells in the field. However, these results also indicate that the performance of reflection concentrators is strongly influenced by environmental conditions, such as light intensity and the reflective characteristics of surrounding surfaces [25]. This emphasizes the importance of selecting the right location and adjusting the design of the reflector concentrator to maximize efficiency. Furthermore, field testing revealed several practical challenges that need to be addressed for widespread implementation of reflector concentrators, such as the need for regular maintenance to keep the reflective surface clean and periodic tilt angle adjustments to compensate for changes in the angle of light incidence throughout the year.

Based on the field experiment results, we also conducted a cost-benefit analysis to evaluate the economic feasibility of using a reflection concentrator. This analysis showed that while there are initial installation and maintenance costs, significant efficiency improvements can offset these costs in the long term through increased energy output and reduced operating costs [26]. In addition, the use of reflection concentrators can also reduce the land requirements for solar cell installations, because more energy can be generated from a smaller area [27]. Environmental implications also need to be considered, as improving solar energy efficiency can reduce reliance on fossil fuels and reduce greenhouse gas emissions. Overall, the field experiment results reinforce the potential of reflection concentrators as a practical solution for improving the performance of bifacial solar cells. These findings provide a strong foundation for broader implementation in the solar energy industry and open up opportunities for further research to optimize the design and application of reflection concentrators under various environmental conditions. Furthermore, these results also demonstrate the importance of a holistic approach in designing and implementing renewable energy technologies, considering technical, economic, and environmental aspects to achieve maximum benefits.

4. Conclusion

In summary, this study successfully designed and tested a reflection concentrator that effectively improves the performance of bifacial solar cells. Through a series of simulations and laboratory and field experiments, we found that the use of a reflection concentrator can increase the efficiency of bifacial solar cells by 15–25%, depending on the environmental conditions and the specific design of the reflection concentrator. The simulation results provide a solid foundation for designing an optimal prototype, while the laboratory and field experimental results confirm the effectiveness of the design in real-world conditions. This significant increase in efficiency is due to the reflection concentrator's ability to focus more light onto the back surface of the solar cell, which is typically less exposed. Furthermore, these results demonstrate that the performance of the reflection concentrator is strongly influenced by parameters such as tilt angle, reflective material, and environmental characteristics, all of which need to be optimized to achieve optimal performance.

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