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MODELLING OF THE PI-SHAPE LOW CONCENTRATING PHOTOVOLTAIC SOLAR CELLS

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ABSTRACT: One of the cheapest ways to improve photovoltaic (PV) systems is to create LCPV systems with polycrystalline silicon solar cells, which require less cost and have high optical efficiency. Additional reflective mirrors were added to improve the optical efficiency of the low concentrating photovoltaic (LCPV) system based on a Fresnel lens. Pi-shaped LCPV cells were obtained and compared with an ordinary LCPV based on a Fresnel lens. The proposed LCPV shows high optical efficiency even at 50 mm of cell-lens distance, while the ordinary LCPV presents a maximum of 30% of optical efficiency. The concentration ratio of 8 suns can be achieved at 150 mm of cell-lens distance at the range ±20° of the incidence angle. When the cell-lens distance is 100 mm or 125 mm, the optical efficiency is more than 80%, and the concentration ratio (CR) is more than 2 suns at the range of incidence angle ±25°. The proposed LCPV design helps to work the system at ±25° without the help of a solar tracking system. Hence, when developing the LCPV system, increasing the acceptance angle might reduce the work of solar tracking systems and the tracking errors. Good irradiance uniformity can be achieved, and the acceptance angle can be increased.

ABSTRAK: Salah satu cara termurah bagi menambah baik sistem fotovoltaik (PV) adalah dengan mencipta sistem LCPV menggunakan sel solar silikon polihabluran, di mana kos lebih rendah dan kecekapan optik tinggi. Bagi meningkatkan kecekapan optik fotovoltaik rendah tumpuan (LCPV) berasaskan kanta Fresnel, cermin pantulan tambahan diperlukan dan bentuk Pi LCPV diperolehi dan dibanding dengan LCPV biasa berasaskan kanta Fresnel. LCPV yang dicadangkan ini menunjukkan kecekapan optik tinggi walau pada jarak 50 mm antara sel dan kanta, manakala LCPV biasa mencapai kecekapan optik maksimum sebanyak 30%. Nisbah tumpuan sebanyak 8 kali pencahayaan matahari dapat dicapai pada jarak 150 mm antara sel dan kanta dalam julat sudut kejadian ±20°. Apabila jarak antara sel dan kanta sebanyak 100 - 125 mm, kecekapan optik adalah melebihi 80% dan nisbah tumpuan (CR) melebihi 2 pencahayaan matahari dalam julat sudut kejadian ±25°. LCPV yang dicadangkan ini dapat membantu sistem beroperasi pada julat sudut ±25° tanpa bantuan sistem penjejak suria. Oleh itu, dengan meningkatkan sudut penerimaan sistem LCPV semasa mencipta sistem, ini berkemungkinan mengurangkan keperluan sistem penjejak suria dan mengurangkan ralat penjejak, mencapai taburan pencahayaan seragam, serta meningkatkan sudut penerimaan secara keseluruhan.

KEY WORDS: *LCPV, Optical efficiency, Fresnel lens, Concentration ratio, Incidence angle*

1. INTRODUCTION

Solar energy is becoming significantly crucial among renewable sources due to its low price and affordability [1, 2]. However, the electrical efficiency of photovoltaic systems today is insufficient to switch to green energy massively, and high-efficiency solar panels are expensive [3]. Researchers are working on increasing the generated energy by PV panels. Several factors affect the performance of PV efficiency, and they are increasing the amount of incident sunlight, cooling the solar cells, and using solar cells with high efficiency [4, 5]. The solar cell's temperature is reduced by applying a cooling system [6]. Using high-efficiency multi-junction solar cells is more expensive and requires a high-precision solar tracking system. There are many types of solar cells [7], and about 90% of the solar cells worldwide are crystalline silicon solar cells [8]. It is considered that one of the cheapest solar cells is polycrystalline silicon solar cells [9]. However, increasing the solar cells' generated energy is a significant task, and several methods exist to solve the problem.

One of the practical methods to increase the incident solar radiation is using solar concentrator optics [10]. Many optical designs for solar concentrators might use mirrors, lenses, and other reflective or refractive optical elements. The paper [11] improved the PV panel efficiency using three mirrors and a cooling system. It proved that the efficiency of solar cells is greatly affected by the amount of solar irradiance. The work [12] modeled the performance of a V-trough concentrating system with a dual-axis solar tracking system. As a result, the overall energy output was increased by 86%, with contributions to both tracking (25%) and concentration (50%). It shows that applying a concentrating optical element improves the system's performance.

According to the concentrating degree, current concentrating photovoltaic (CPV) cells are divided into low, medium, and high CPV cells [13]. Optical elements of high-concentration photovoltaic (HCPV) systems concentrate sunlight into one small point to achieve a higher concentration ratio (more than 300 suns), which leads to the use of small solar cells, such as multi-junction solar cells, which are not affordable. Low concentrating photovoltaic (LCPV) and medium concentrating photovoltaic (MCPV) systems can be designed with cheaper silicon solar cells [14]. LCPV systems benefit from their simplicity and affordability.

Low concentrating photovoltaic (LCPV) systems, which have a 1:10 concentration ratio, are considered simple in optics, can be made with affordable materials, and do not require a high-accuracy solar tracking system. Currently known LCPV optics [15] are V-trough [16], parabolic concentrators [17], cylindrical troughs, and linear Fresnel reflectors [18]. The paper [19] has designed a 7-sun low-concentration CPV system based on compound parabolic concentrators. The work [20] showed that 2x V-Trough LCPV with a seasonal tracking system can generate 44% higher energy output than a flat PV panel. Much research has been done on low-concentration photovoltaic systems with different designs of concentrating elements [21, 22].

One of the concentrating elements for LCPV is Fresnel lenses, and today, some work is being done on improving LCPVs based on Fresnel lenses. The works [23, 24] showed that when using a Fresnel lens as a concentrator for polycrystalline solar cells, it is possible to get an LCPV panel that can generate 27% more energy than a non-concentrated silicon solar panel. It is certain that when using a Fresnel lens, the hot spot occurs in the center of the solar cell, which degrades its reliability and conversion efficiency. To mitigate damage caused by hot spots and enhance the acceptance angle, Fresnel concentrators typically incorporate an additional concentrator called a secondary optical element (SOE). This integration aims to

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improve the acceptance angle and achieve a more uniform energy distribution, thereby addressing hot spots and ensuring efficient sunlight concentration [25].

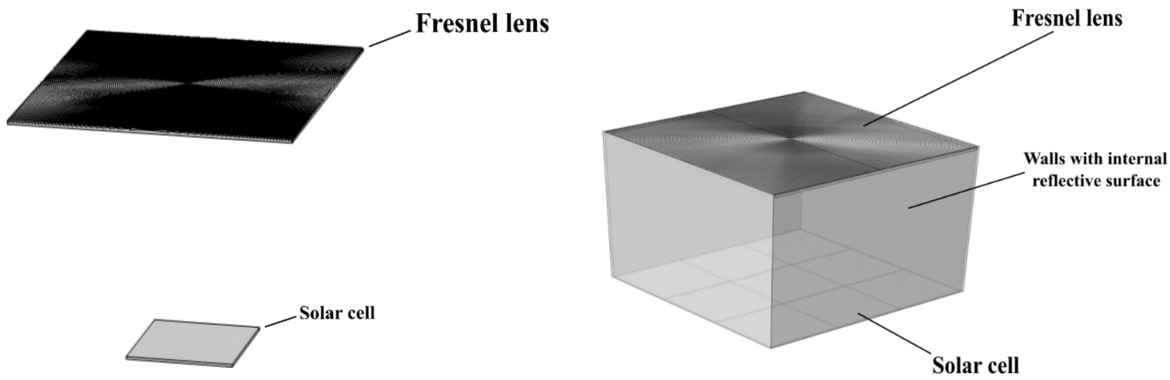
Another paper [26] presented a complete optical modeling to improve the simulation of an ordinary Fresnel lens with a refractive secondary optical element (SOE) and found that the pyramid has high optical efficiency and a more uniform irradiance distribution. The CPC has a large acceptance angle but shows the least uniformity. However, most of the work is done for HCPV systems with multi-junction solar cells, and those systems need a solar tracker because they cannot work at high incidence angles [27]. Their optical efficiency is 90% up to an incident angle of 0.4°, then reduced to 80% at 0.6°, and then to 10% at 1° [28]. This work will use polycrystalline silicon solar cells, which are several times cheaper than multi-junction solar cells. Reflective surfaces will be used as additional optical elements.

Increasing the acceptance angle refers to the ability of the concentrator to capture sunlight from a wider range of incidence angles [29]. The problem is that when the incidence angle increases, the sunlight flux on the solar cell decreases, reducing the number of photons on the solar cell and the output current of the cell array. To overcome the problem, a solar tracking system is usually applied, and the concentrating PV systems will be oriented to the Sun. However, the solar tracking systems require external power consumption, affecting system costs. Therefore, we propose reducing the work of solar tracking by concentrating optics. To do this, optimal parameters of the optical system must be found. This work proposes a design of LCPV based on a Fresnel lens and Pi-shaped reflective surfaces with nine silicon solar cells, which can reduce the work of a solar tracking system at a specific range of incidence angles. The optimum distance between the lens and the solar cell is significantly affected by the relation between the concentrating optics and the solar cell [30]. The proposed system is compared with an LCPV with only a Fresnel lens without mirrors and a single solar cell. The novelty of the work is to increase the optical efficiency and widen the incidence angle of ordinary Fresnel-based LCPV using reflective mirrors. One of the study's aims is to identify the optimal cell-lens distance and calculate the optical efficiency at different incident angles. Due to the proposed design, the low-concentration optical system can show good optical performance at higher incidence angles.

2. METHODOLOGY

The solar cell and the optics must be compatible within the module [30]. The solar cell used in this work is a polycrystalline silicon solar cell. The commercial silicon solar cells are used under a concentration from 2 suns to 10 suns, as the electrical performance of a polycrystalline silicon solar cell is limited by the recombination losses, which limit the open-circuit voltages. The losses increase proportionately at higher illumination [31]. Our previous works [23, 24] proved that a polycrystalline silicon solar cell can work with a Fresnel lens at an optimal distance shown in Figure 1(a) and convert 27% more electrical energy than a non-concentrated solar cell. In this work, the modified structure of the system is proposed.

Figure 1 (b) shows this work's proposed Pi-shape LCPV design. It consists of a Fresnel lens and four (4) reflective surfaces. The LCPV system has nine (9) solar cells, which can help harvest more sunlight from inclined rays compared to a single solar cell at wider incidence angles.



(a) (b)

Figure 1. (a) A solar cell with a Fresnel lens, (b) the Pi-shape system based on a Fresnel lens and a reflective surface with nine solar cells.

LCPV systems with concentrating optical systems based on Fresnel lenses require a solar tracking system because Fresnel lenses have a point focus. This means that the systems cannot work from a wider angle of incidence. The concentrated sunlight spot is to the side of the solar cell; therefore, adding additional solar cells around the main solar cell helps prevent the concentrated sunlight at high incidence angles. The cost of polycrystalline solar cells is not expensive; therefore, using nine solar cells instead of one doesn't affect the total cost of the system much, since using a single solar cell with a Fresnel lens requires a high-accuracy solar tracking system, which costs more than fixed solar panels [32].

Moreover, reflective mirrors do not show chromatic aberration, and high optical efficiencies can be achieved [33]. Therefore, reflective surfaces redirect the shifted sunlight flux to the solar cells. The size of the reflective mirrors depends on the cell-lens distance of the system.

COMSOL Multiphysics is used in simulation to assess the proposed system. The geometrical parameters of the system used in COMSOL Multiphysics are presented in Table 1.

Table 1. Parameters of the LCPV system

Types of Vehicle	Value
Size of the Fresnel lens, mm^2	150×150
Reflective index of the mirror	1
Size of the Solar cell, mm^2	50×50

The simulation illuminated the CPV system under a DNI of 1000 W⁄m2. A 50×50 mm polycrystalline silicon solar cell is used. The size of the Fresnel lens was 150×150 mm, and the optimal size of reflective surfaces had to be found depending on the system's optical performance at different cell-lens distances. To simulate the model, 5776 rays were set to produce the results. The ray-tracing method was used to simulate and optimize lenses and reflectors.

Figure 2 presents the work process in COMSOL Multiphysics as a block diagram. In this work, a ray tracing simulation was conducted using the Geometrical Optics module of the COMSOL Multiphysics software package. In the Geometrical Optics module, electromagnetic waves are treated as rays, and ordinary differential systems are solved, determining each ray's location and wave vector for individual parts of the 3-D model.

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The boundary conditions for the simulation were: 1) for the Fresnel lens, it was a refractive interface that allows light refraction and focusing and works according to Snell's Law; 2) mirror reflection was used for reflective mirrors, and the purpose was to reflect rays toward the cells; 3) an absorbing surface was used for detectors to capture the rays. Moreover, a steady-state method was used for ray-tracing simulations, which does not include any dynamic changes in optical properties. Ray tracing uses numerical calculations to model and is performed by solving Hamilton's equations.

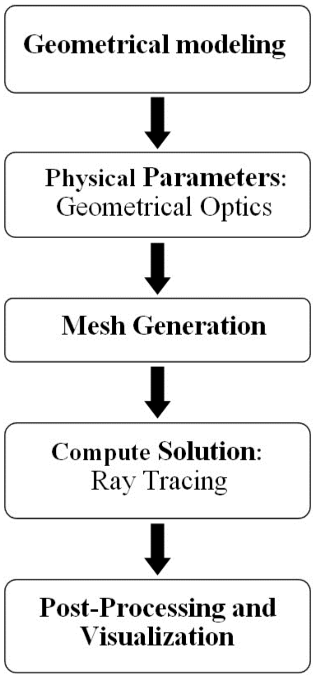


Figure 2. Block diagram of COMSOL Multiphysics.

To evaluate optical performance, the optical system is tested at different incidence angles, cell-lens distances, and geometrical parameters [34]. Finding optimal optical efficiency and concentration ratio at different incidence angles is a significant task; therefore, to fully characterize a given optical system, it is necessary to assess optical efficiency and concentration ratio parameters. The optical efficiency η_{op} of a lens can be defined as the ratio of radiant power at its input aperture P_{in} which reaches its output P_{out} or, in our case, the ratio of the number of entered rays to the number of incident rays on the surface of the solar cells [33].

$$\eta_{op} = \frac{P_{in}}{P_{out}} = \frac{N_{ent}}{N_{exit}} \tag{1}$$

The geometrical concentration ratio is defined as the ratio of the input area A_{in} (in our case, the area evaluated at the lens's input aperture) to the output area A_{out} (i.e., the area evaluated at the receiver area) [34].

$$C_g = \frac{A_{in}}{A_{out}} \tag{2}$$

The optical concentration ratio of the system is calculated by the following equation and is measured with the sun:

$$CR = \eta_{op} \cdot C_g \tag{3}$$

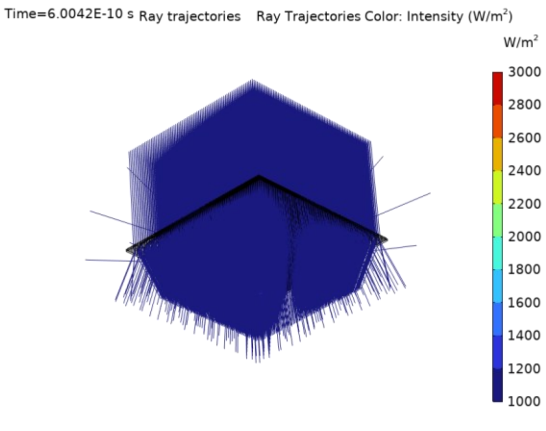
The optical parameters of the optical system will be calculated and analyzed using Eqs. (1)-(3).

3. RESULTS AND DISCUSSION

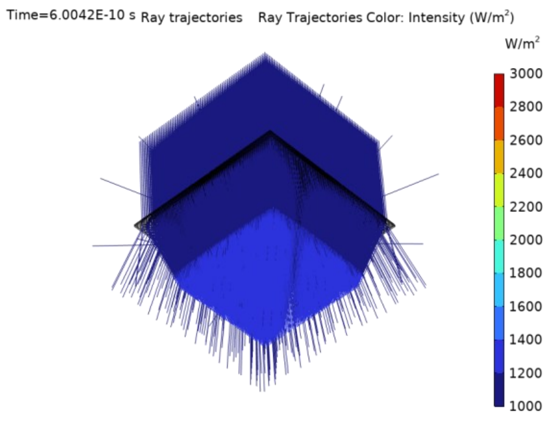
3.1. Results

Simultaneously, simulations in COMSOL Multiphysics for both systems were conducted to evaluate the proposed LCPV system and compare it with an ordinary LCPV with just a Fresnel lens. The results from the ray tracing simulation were plotted, as shown in Figure 3.

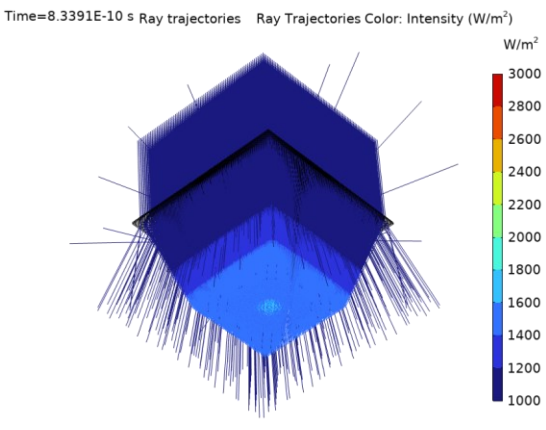
The incidence angle of the rays was zero degrees in this simulation. The results show that if the rays are perpendicular to the Fresnel lens surface with reflective mirrors, the central solar cell receives more concentrated sunlight as the cell-lens distance increases. The length of the light spot increases by decreasing the cell-lens distance. In the simulation, the results of an ordinary LCPV with only a Fresnel lens show that some rays are not concentrated. In contrast, in the proposed system, the rays are concentrated and shaped rectangularly due to reflective mirrors. The proposed LCPV system can collect all rays perpendicularly and at some incidence angles. Figure 4(e) shows that the Fresnel lens at 150 mm from the solar cell increases the solar radiation from 1000 W/m^2 to 3000 W/m^2. It means the optical concentrator can help to increase the sunlight power 3 times compared to without the concentrating element, since the proposed concentrating system gathers sunlight from a larger area and directs it to a smaller solar cell surface.



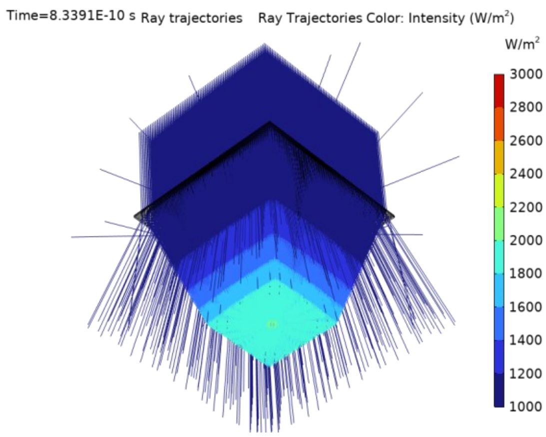
(a) 50 mm



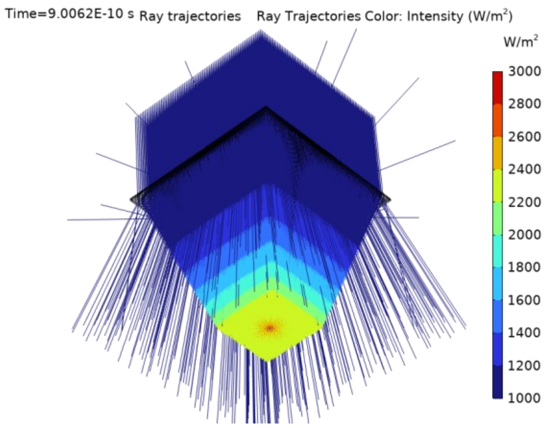
(b) 75 mm



(c) 100 mm

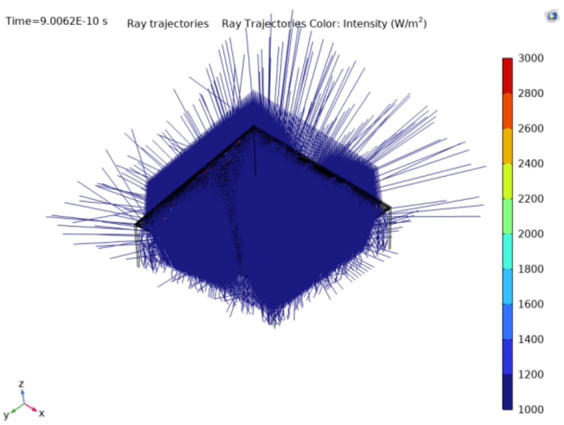


(d) 100 mm

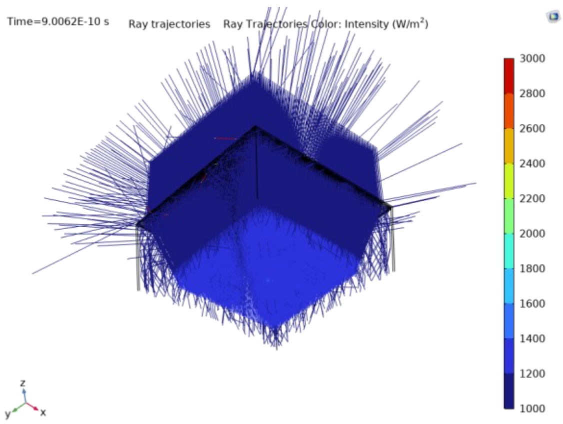


(e) 150 mm

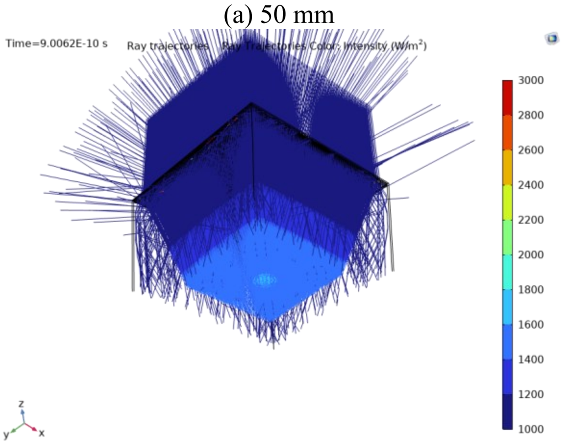
Figure 3. Ray trajectories at different cell-lens distances of ordinary optical systems



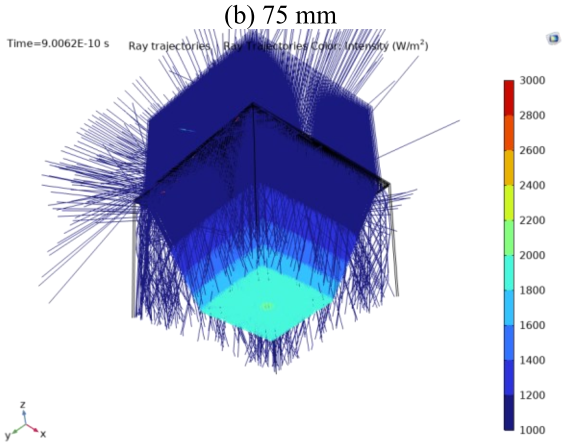
(a) 50 mm



(b) 75 mm



(c) 100 mm



(d) 100 mm

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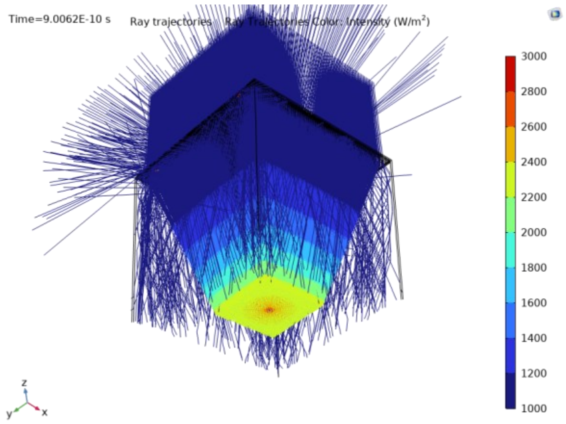
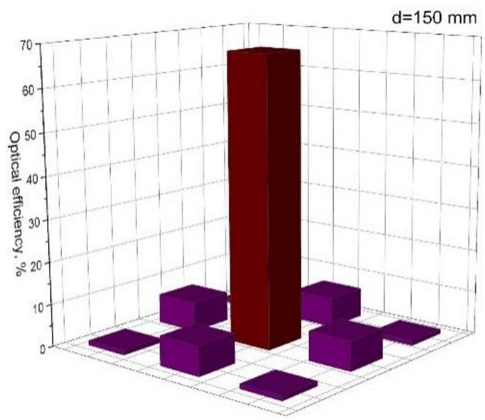


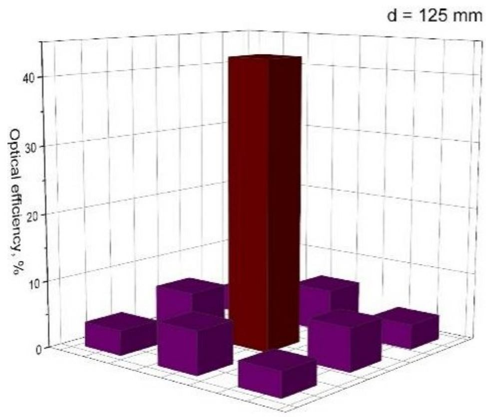
(e) 150 mm

Figure 4. Ray trajectories at different cell-lens distances of the proposed LCPV design.

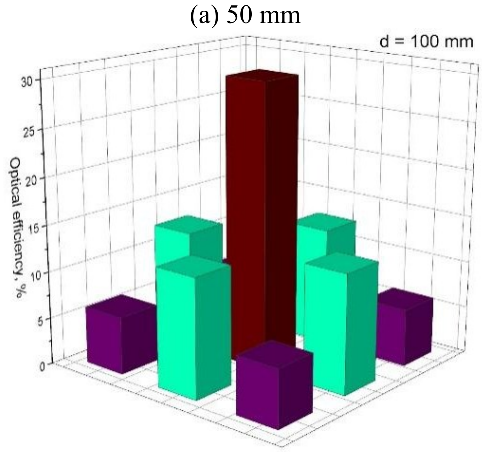
As the Fresnel lens has a point focus, the sunlight is concentrated more on the central part of the solar cells. Figure 5 shows the distribution of incident sunlight flux on the surface of solar cell arrays at a zero incidence angle. When the Fresnel lens is closer to the array, the sunlight is concentrated on the central solar cell and the other eight solar cells. The closer to the center, the more optical efficiency they gain. Solar radiation is mostly concentrated on the central solar cell at 150 mm (Figure 5 (a)) since the optical efficiency of the central solar cell is higher than that of the other solar cells. At 125 mm (Figure 5 (b)), the optical efficiency of the central solar cell is still much higher than that of the other cells, but lower than at 150 mm. At 100, 75, and 50 mm, the optical efficiency of the four solar cells around the central one is higher than that of the four solar cells at the four corners of the module (Figure 5 (c, d, e)).



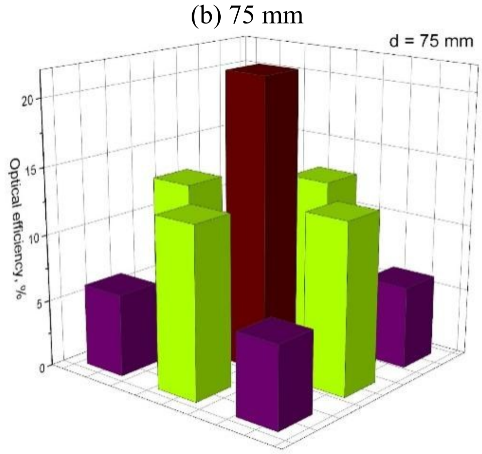
(a) 50 mm



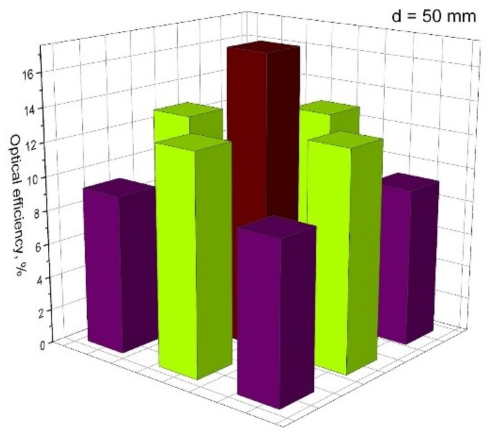
(b) 75 mm



(c) 100 mm



(d) 100 mm

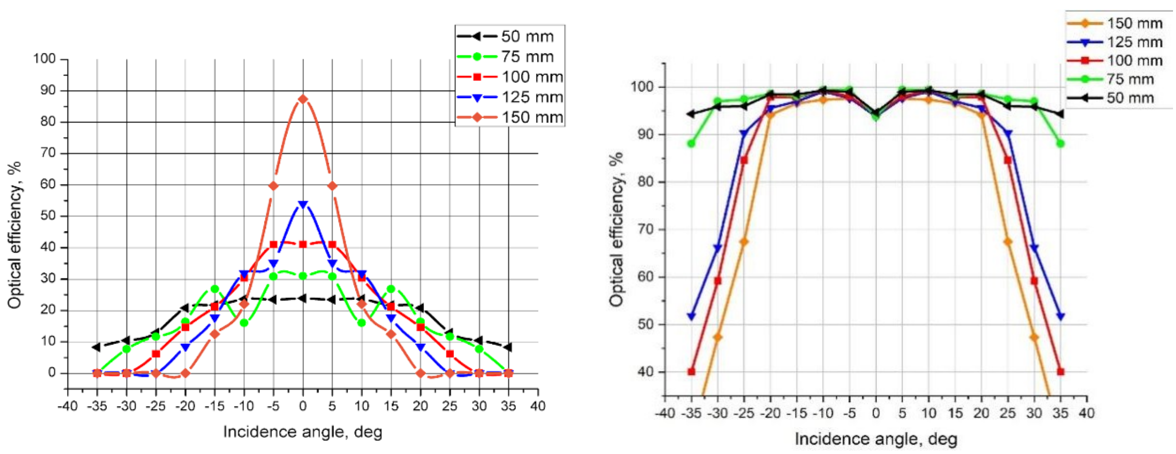


(e) 150 mm

Figure 5. Optical efficiency in the area of nine solar cells at different cell-lens distances.

As the solar cell is located at the center of the Fresnel lens, there is always high optical efficiency at a zero incidence angle. Both ordinary and proposed systems were simulated at a range of ±35° of the incidence angle. In Figure 6a, it can be seen that the LCPV with an ordinary design has approximately 90% optical efficiency at only a zero incidence angle, and when the incidence angle is ± 5°, the optical efficiency falls to 60% at 150 mm cell-lens distance. Moreover, at other cell-lens distances and incidence angles, the optical efficiency is very low. The proposed LCPV design shows good optical performance at wider incidence angles (Figure 6 (b)).

Increasing the cell-lens distance decreases the width of the concentrated light spot. When the incidence angle increases, there is a significant increase in optical efficiency from approximately 95% to 99% (Figure 6 (b)), which means redirecting rays using reflective mirrors can improve the optical efficiency at a certain range of incidence angles. The optical system has a range of incidence angles for which the optical efficiency of the optical system is higher than in the case of a zero incidence angle. For nonzero incidence angles, the incoming sunlight undergoes side reflections, which increase the chances of light being redirected towards the solar cells, meaning that the reflective mirrors help trap more sunlight, reducing optical losses.



(a) Ordinary Design (b) Proposed Design

Figure 6. The dependence of optical efficiency on the incidence angles at different cell-lens distances.

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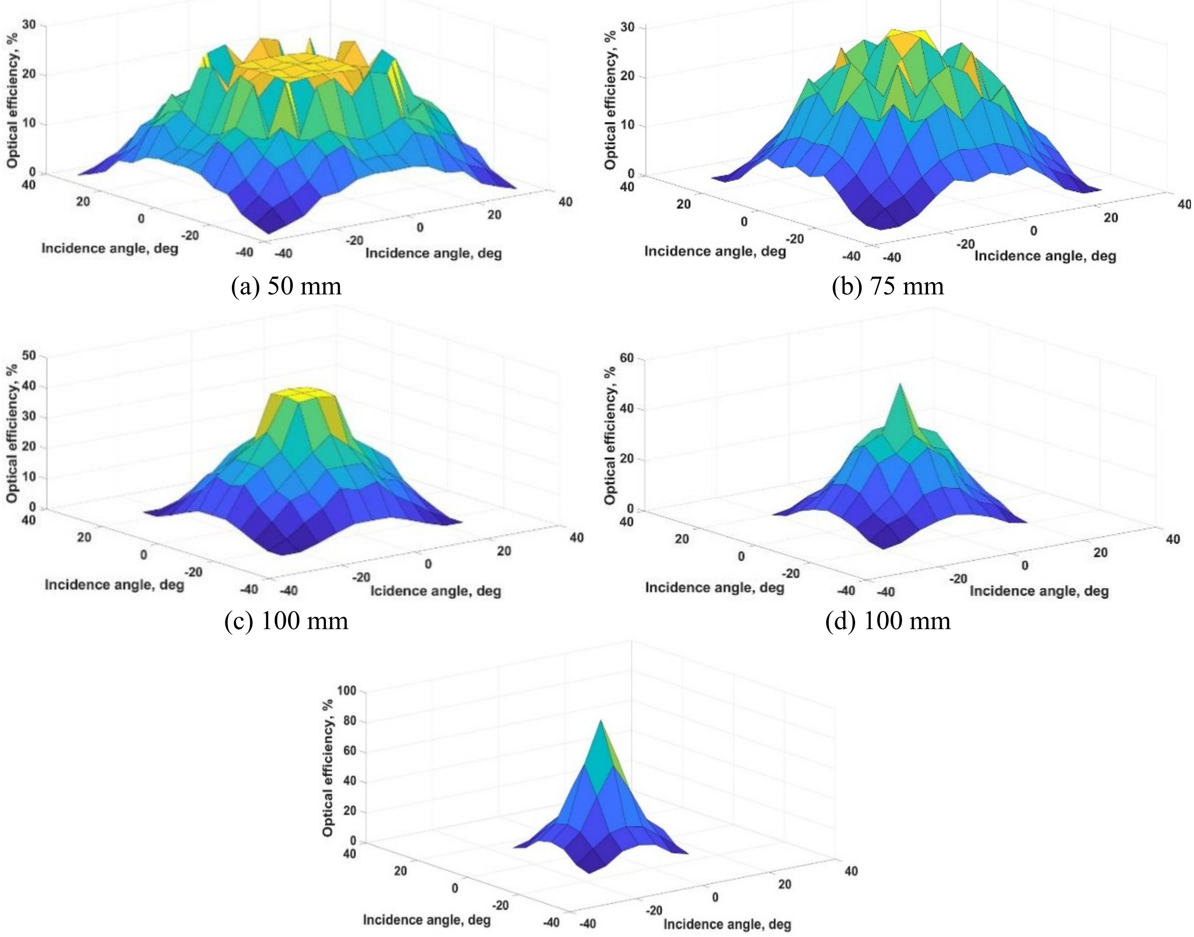
Figures 7 and 8 show the optical efficiencies of ordinary LCPV and proposed LCPV systems at different incidence angles in 3-D. The proposed LCPV shows high optical efficiency even at 50 mm of cell-lens distance, thanks to the reflective mirrors and nine solar cells. At the same time, the ordinary LCPV presents a maximum of 30% optical efficiency (Figure 7 (e), 8 (e)).

It can be seen in Figures 6 and 8 that the proposed optical system can achieve high optical efficiency in the range of ±20° of the incidence angle. However, optical efficiency is also affected by cell-lens distance. It is possible to achieve more than 85% optical efficiency when the cell-lens distance is 75mm, 50 mm in the range of ±40° of incidence angle (Figure 8 (d, e)). In the case of cell-lens distances are 100, 125, 150 mm, at more than ±20° As the incidence angle increases, the system's optical efficiency decreases gradually (Figure 8 (a, b, c)). The results suggest that the higher the optical efficiency at wider incidence angles, the shorter the cell-lens distance. A larger cell-lens distance makes the system more sensitive to the incidence angle, as the concentrated light spot may shift away from the solar cell area.

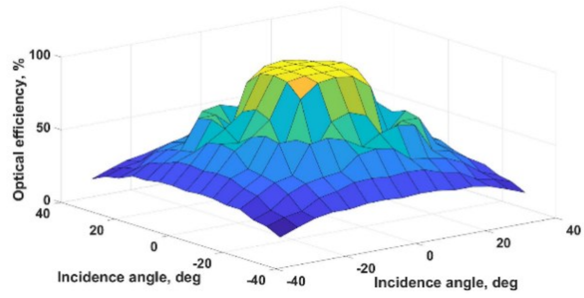


(a) 50 mm (b) 75 mm

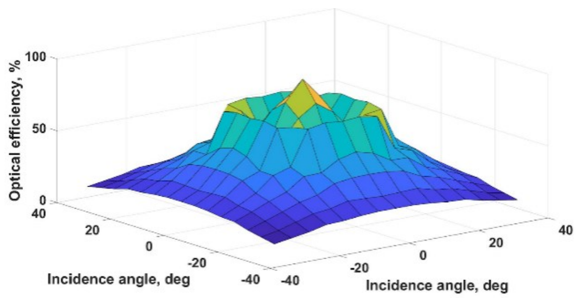
(c) 100 mm (d) 100 mm

(e) 150 mm

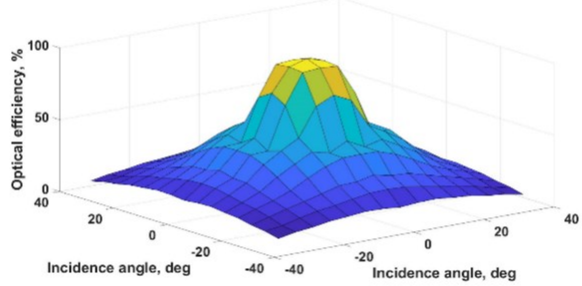
Figure 7. The three-dimensional dependence of optical efficiency on the incidence angle at different cell-lens distances of the ordinary LCPV.



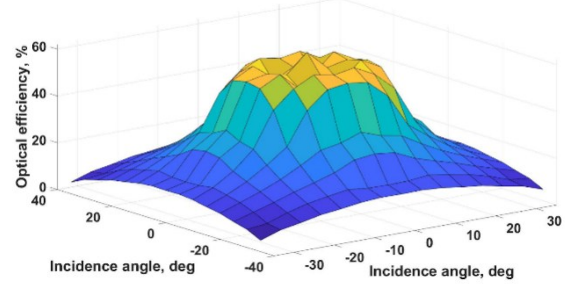
(a) 150 mm



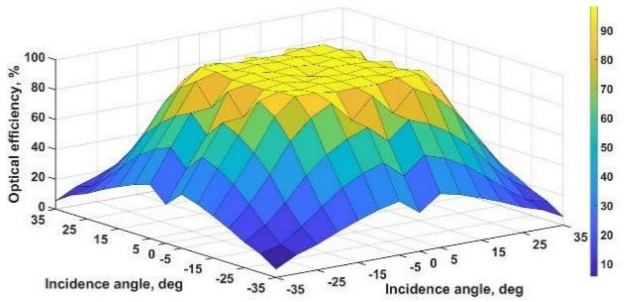
(b) 125 mm



(c) 100 mm

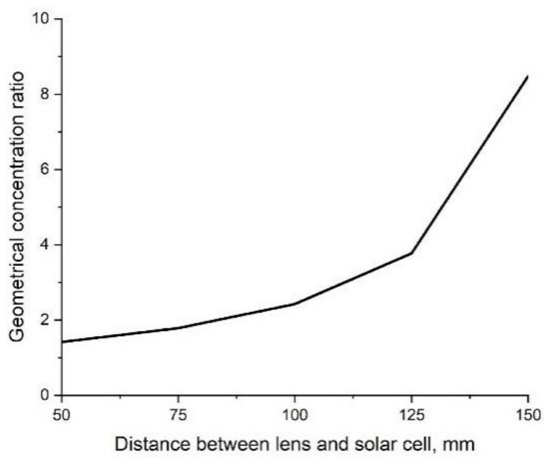


(d) 75 mm

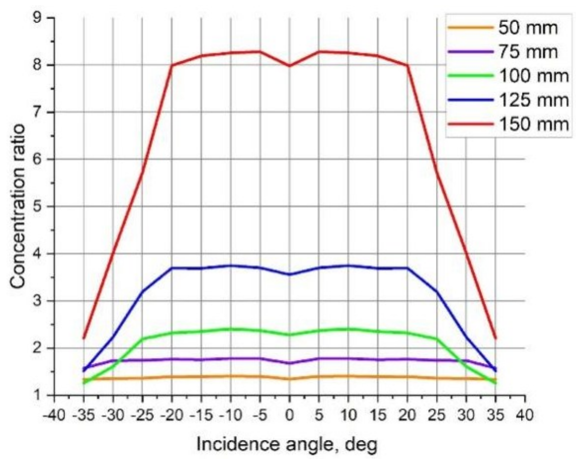


(e) 50 mm

Figure 8. The three-dimensional dependence of optical efficiency on the incidence angle at different cell-lens distances of the proposed LCPV.



(a) Cell-lens distance



(b) Incidence angle

Figure 9. Dependence of the concentration ratio

Figure 9 shows the calculated results by Eq. (2), and if the Fresnel lens is closer to the solar cells, the geometrical concentration ratio reduces. In Figure 9a, the geometrical concentration ratio reaches 8.4 if the cell-lens distance is 150 mm, but at this distance, the optical efficiency reduces sharply if the incidence angle is more than ±20°. Figure 9(b) shows the results calculated by Eq. (3).

A concentration ratio of 8 suns can be achieved at 150 mm of cell-lens distance at the range ±20° of the incidence angle. At 50, 75 mm, the system cannot reach 2 suns, but optical efficiency is always high at ±35° of the incidence angle. When the cell-lens distance is 100, 125 mm, the optical efficiency is more than 80% and CR is more than 2 suns in the range of incidence angle ±25°. The proposed LCPV design helps to work the system at ±25° without the help of a solar tracking system.

3.2. Discussion

Many Fresnel lens-based concentrating photovoltaics cannot work at incidence angles more than ±1.5° and work with small multi-junction solar cells [35]. Therefore, they require a high-accuracy solar tracking system, which might incur extra costs. Another main cost of the CPV systems comes from the solar cells [36]. Many Fresnel-based concentrating photovoltaics use expensive multi-junction solar cells [37, 38] while in this work, polycrystalline silicon solar cells were used, which are the cheapest solar cells. These solar cells can work at low and medium concentrations [14], and in this work, low concentration is achieved using a Fresnel lens and reflective mirrors. Our previous works achieved low concentration [23, 24] and could get 27% more energy, but the proposed LCPV has more advantages than our ordinary system. In the proposed LCPV, the rays are concentrated and shaped as a rectangle due to reflective mirrors, and the geometrical concentration ratio reached 8.4 when the cell-lens distance was 150 mm. One of the advantages of the proposed system is that when the incidence angle increases, there is a significant increase in optical efficiency from approximately 95% to 99% (Figure 6(b)), it means redirecting rays by using the reflective mirrors can improve the optical efficiency at a certain range of incidence angles. Moreover, the proposed LCPV shows high optical efficiency at 50 mm of cell-lens distance, while the ordinary LCPV presents a maximum of 30% of optical efficiency. The next advantage of the proposed system is that the proposed optical system can have high optical efficiency at the range ±20° of the incidence angle. Subsequently, the concentration ratio of 8 suns can be achieved at 150 mm of cell-lens distance at the range ±20° of incidence angles. When the cell-lens distance is 100, 125 mm, the optical efficiency is more than 80%, and CR is more than 2 suns at the range of incidence angle ±25°. Finally, the proposed LCPV design helps to work the system at ±25° without the help of a solar tracking system.

Hence, by increasing the acceptance angle of the LCPV system, it might be possible to reduce the work of solar tracking systems, reach irradiance uniformity, and increase the acceptance angle. This system can reduce the maintenance of CPVs, extend the effective operating hours of the LCPV, as it can capture tilted incoming sunlight, and with ±25° tolerance, the system may perform better in partially cloudy weather conditions.

4. CONCLUSION

LCPV was designed, simulated, and tested using a Fresnel lens and reflective surfaces with nine polycrystalline silicon solar cells. The proposed optical system is called a Pi-shape concentrating optical design. The proposed LCPV design was compared with an ordinary Fresnel lens-based LCPV without mirrors. Both systems are made with polycrystalline silicon solar cells, which are more affordable than multi-junction solar cells. The proposed system doesn't lose rays since the reflective mirrors redirect the sunlight, and the redirected rays hit any of the nine solar cells. Ordinary LCPV can show high optical efficiency only when the cell-lens distance is 150 mm, and when the incidence angle increases, there is a sharp fall in optical efficiency. The proposed optical system could improve the optical efficiency approximately from 95% to 99% at the range ±15° of the incidence angle. Optical efficiency of the system is more than 85% when the cell-lens distances are 75mm and 50 mm, and the incidence angle is in the range of ±40°. When the cell-lens distance is 100 or 125 mm, the optical efficiency is more than 80%. CR is more than 2 suns at the range of incidence angle ±25°. Due to high optical efficiencies at higher incidence angles, the proposed LCPV with mirrors can work without a solar tracking system, reducing the system's manufacturing cost in the future.

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