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Research Paper

Analysis and Implementation of a New Method to Increase the Efficiency of Photovoltaic Cells by Applying a Dual Axis Sun Tracking System and Fresnel Lens Array

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Abstract

Nowadays conversion efficiency of photovoltaic (PV) equipment is considered as an important issue. In this article, the effects of a semi-Fresnel lens as a convergent structure will be simulated in COMSOL Multiphysics software and the results would make improvements in the characteristic responses of PV cells which are verified with our experimental results. Besides, because the groove angles of the semi-Fresnel lens are calculated based on the orthogonal sun rays, a novel dual-axis sun tracking system has been designed and constructed for panel orientation adjustment. So, the sun rays always radiate at the same efficient angles on PV cells. This issue leads to a reduction in light concentration area, the total area of the cells and their costs. Results show a significant improvement in output power of the PV cells array in comparison to the previous study by more than 2.5 times. Also, the effective time of cell performance from sunrise to sunset, extends longer during a day, regardless of location and time zone.

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1. INTRODUCTION

The efficiency of PV cells is immensely low in a unit of area and expenses because of tremendously different effective parameters such as thermal waste, shading, spectral responses of modules, and so on. In addition, researchers have been working on improving the characteristic responses of the PV cells to use them efficiently in various applications. The concentration of sun rays is caused to enhance the PV cell performances and reduce total cells' area and their cost which are focused on a small area of the PV cells through the parabolic solar concentrator, linear refractive Fresnel lens, reflectors with dish-shaped structure [1]-[2] white light separation through a Fresnel lens in order to light absorption with specific materials (with different band gap) [3]. Recently, researchers have been focusing on the design and Fresnel lens improvement structure because of its small volume, low weight, light focusing, and high intensity of the solar rays, high efficiency, and simply affordable [4]-[9] which makes commercialize to harness in a wide range of applications especially for power consumption supplies in space missions [3]-[5]. Also, optimization of Fresnel lens structure, which is based on simulations' consequences, has been carried out as a beneficial tool in the research approaches among reducing errors, designs enrichment and output efficiency, time likewise construction costs [10]-[12]. On the other hand, sometimes secondary optical elements can be applied because of the system efficiency enhancement based on a uniform distribution of the sunlight flux on the panel surface. Furthermore, Fresnel lens usage array along with a sun tracking system has led to improved PV cell performance according to adjusting the PV panel in an optimized direction relative to the sun position [6], [13]-[14].In the other words, the sun tracking system adjusts the solar panel surface perpendicular to the entrance sun rays to use sunlight efficiently. This system generates a trajectory of module movement for sun tracking action contingent on longitude and latitude, the season, time, sunrise and sunset, height from sea level, azimuthal, and sun height angle, etc.[6], [13],[15]-[18]. So, the fixed solar panels would be equipped with single or dual-axis sun tracking systems with the aim of efficiency increment in order to apply equipment, their features, and condition [17], [19]-[20] Moreover, an automatic cleaning module harnessing alongside a single-axis sun tracking system can improve the PV cell array output power up to 15 % [16]. Focusing on our previous studies in the laboratory, a novel refractive structure, a semi-Fresnel lens array had been designed and constructed by calculating the groove angles of Fresnel lens according to the refraction and convergent angles of the orthogonal incident ray from transparent material, named PLEXIGLAS [6]. As far as all calculations are concerned the orthogonal incident angles of the sun rays to the flat side of the applied lens surface, a manual prototype sun tracking module was applied to adjust the panel perpendicular so that the sun rays incidence [6].

In this article, at first glance, Fresnel lens effects on output characteristic responses of a single monolayer silicon solar cell have been simulated under a standard solar spectrum (AM 1.5) in 40 various wavelengths as a rough spectrum with aiding of COMSOL Multiphysics software [21] based on finite element method. The results reveal in satisfactory agreement with previous experimental studies in our laboratory [6] and demonstrate good improvement in the characteristic response of the PV cell.

Following this, a new dual-axis sun tracking system is designed and constructed for better and accurate performance with special features. Consequently, the experimental setup of this study includes a PV panel (placed in the focal distance) plus previous convergent structure, semi-Fresnel lens array [6], and a new dual-axis sun tracking system. Meanwhile, the dual-axis sun tracking system can track the sun's position according to the parameters at different times of the day so that adjusting the PV panels precisely in the proper orientation (perpendicular to the sun rays). Thus, improvement in output characteristics reveals among responses and PV cell array efficiency, on account of well-organized utilization in sunlight for prolonged hours through the day and loss reduction.

2. MATERIAL AND METHOD

A. Simulation of Fresnel Lens Effect

A schematic diagram of semi-Fresnel lens performance as a convergent structure is illustrated in Fig. 1. In the first step of the simulation, a monolayer silicon solar cell P-N junction with 20 µm x 1 µm dimension was exposed to a standard solar radiation spectrum (AM 1.5) in 40 different wavelengths as a rough spectrum in the COMSOL Multiphysics software package [21]. A uniform doping of P-type which is formed on N-type silicon wafer with $1.0\text{x}10^{16}$ cm^{-3} density and peak P-type concentration of $1.0\ \text{x}10^{19}$ cm^{-3} on the other surface leads to a depletion layer (in range of µm) under normal conditions as a consequence of photo-generated carriers sweeping. Additionally, by applying a small forward bias voltage, evaluation of the characteristic responses of defined PV cells were put through as "I_V" and "output power" curves. It can be noted that simulation of solar cell performance can be considered as an important tool in the cell manufacturing process [22]-[25]

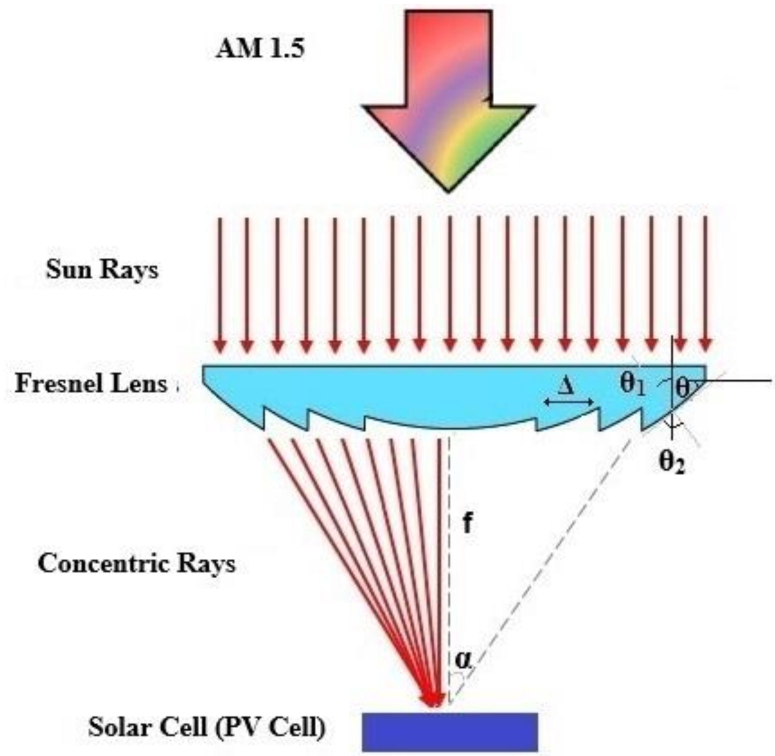


Fig. 1. Simple schematic diagram of the semi-Fresnel lens function

In the next step, a Fresnel lens was designed in the geometry section in the COMSOL environment based on the first simple spherical lens with 50 µm diameter and 150 µm focal length with 16 digitized levels step by step stand on mλ/(n-1) formula (where λ wavelength and n refractive index) [21]. Besides, the designed Fresnel lens geometry is configured by the above method in COMSOL Multiphysics software in the geometry section, shown in Fig. 2 with magnification. As illustrated in Fig. 1, the sun rays enter the lens from the flat side, pass through its ambient, and exit from the other side. Then, these rays are concentrated on a small area. So, the output power distribution of this section in focal length was given to the defined monolayer silicon solar cell as an initial condition for evaluation in semi-Fresnel lens effects on output characteristic responses of the PV cell.

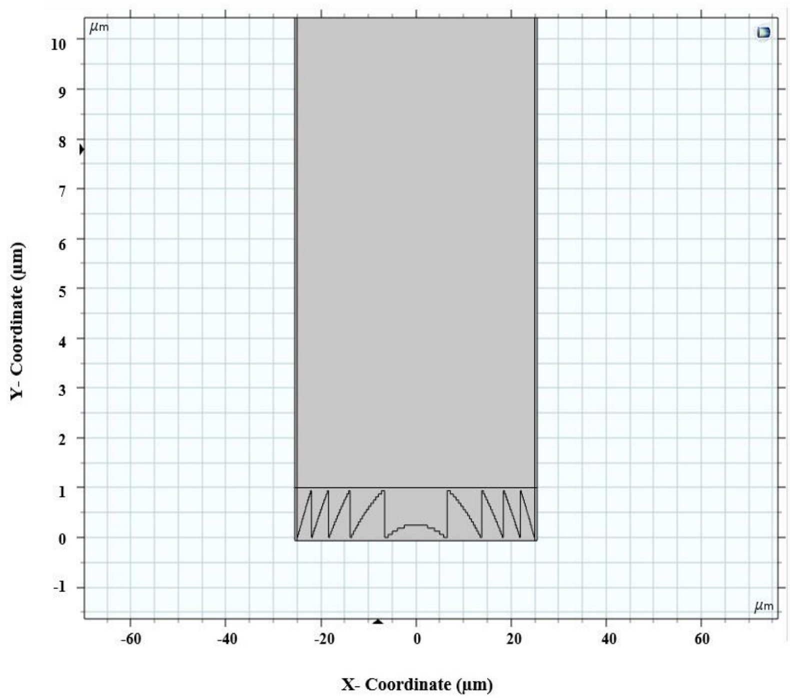


Fig. 2. Configuration of designed Fresnel lens geometry based on the first simple spherical lens in COMSOL Multiphysics software

B. Characteristic Parameters of the PV Cell and Fresnel lens

Output characteristic parameters of PV cells, such as output current through a load and fill factor are calculated by using Eq. (1) and Eq. (2) [26]:

$$I_{out} = N_p I - N_p I_s \left[\exp\left(\frac{qV_{out} + RsI_{out}}{N_s KAT}\right) - 1 \right] - \frac{V_{out} + I_{out} Rs}{R_{sh}} \tag{1}$$

And fill factor is:

$$FF = \frac{I_{MP} V_{MP}}{I_{sc} V_{oc}} \tag{2}$$

I_{MP} and V_{MP} are current and voltage where output power is maximum and also I_{sc} and V_{oc} are short-circuit current and open-circuit voltage [26] respectively.
But for concentrating the light on the PV cell by aiding of the semi-Fresnel lens, angles of the grooves have been evaluated based on Snell's law with a focal length of f. If the light beam makes the angle of θ_1 with the orthogonal line relative to the groove, refracts with an angle of θ_2 relative to the same orthogonal line and makes an angle as α with a focal line for the orthogonal incident rays (as referred in Fig. **1**) and also non-orthogonal angles which is calculated by using Eq. (3)-(5) consider as loss [6]:

$$n_1 \operatorname{Sin} \theta_1 = n_0 \operatorname{Sin} \theta_2 \tag{3}$$

$$\theta_1 = \theta, \theta_2 = \theta + \alpha \tag{4}$$

$$n_1 \operatorname{Sin} \theta = n_0 \operatorname{Sin}(\theta + \alpha) \tag{5}$$

Where n_0 in above equations is the refractive index of the air and can be set equal to 1 and also n_1 is the refractive index of the medium where for PLEXIGLAS is near 1.49 and used for α calculation by using Eq. (6)-(7) as referred in [6]:

$$\operatorname{Sin} \alpha = \frac{(N - 1 + \frac{N}{2})\Delta}{\sqrt{\left((N - 1 + \frac{N}{2})\Delta\right)^2 + f^2}} \tag{6}$$

$$\alpha = \operatorname{Sin}^{-1}\left(\frac{(N - 1 + \frac{N}{2})\Delta}{\sqrt{\left((N - 1 + \frac{N}{2})\Delta\right)^2 + f^2}}\right) \tag{7}$$

Where Δ is the width of each groove and N is the number of grooves counting from the center part [6]. So in this article, a previously constructed convergent array of the semi-Fresnel lens is applied and a prototype sun tracking system (as used in [6]) is replaced with a new improved dual-axis sun tracking module.

C. Dual-axis Sun Tracking Module

The efficiency of the PV cell is maximum for the perpendicular rays regarding the module surface and also calculations of the lens parameters which is subjected to these rays, can be calculated by using Eq. (3)-(7). So, in this study, the new dual-axis sun tracking system is designed and constructed in order to enhance PV cells' performances through efficient sunlight usage during the day. In truth, this sun tracking system tends to adjust the PV panel or flat side of the lens perpendicular to the entrance sun rays with better precision relative to the sun position. Single-axis tracking systems with cheaper prices and even simpler construction consist of lower efficiency [19] in comparison with two-axis systems which depend on an azimuthal elevation or a polar tracking method [20] . The azimuthal elevation method is a common method, remarkably in systems with large dimensions as a consequence of proper rotation in four main directions, while the polar tracking system is the most common method in small PV modules. Furthermore, different types of these systems include both the closed-loop control system, which depends on higher power consuming photo-sensors, and the open-loop control systems which are restricted by predefined trajectory algorithms [17]. In this essay, the controlling program of the new dual-axis sun tracking system has been followed up by calculating the trajectories in order to change the orientation of the panel perpendicular to the sun rays all the time which depend on the height and azimuthal angle. Above all, these angle calculations are according to the parameters such as longitude, latitude, season, time, sunrise, sunset, sun position relative to the panel, local astronomical data, and daily sun trajectory for changing panel orientation. Also, the tracker system might use available astronomical databases to determine the sun position in different time zones and locations with the help of a microcontroller and determining a panel orientation in four main direction directions [27]-[28].

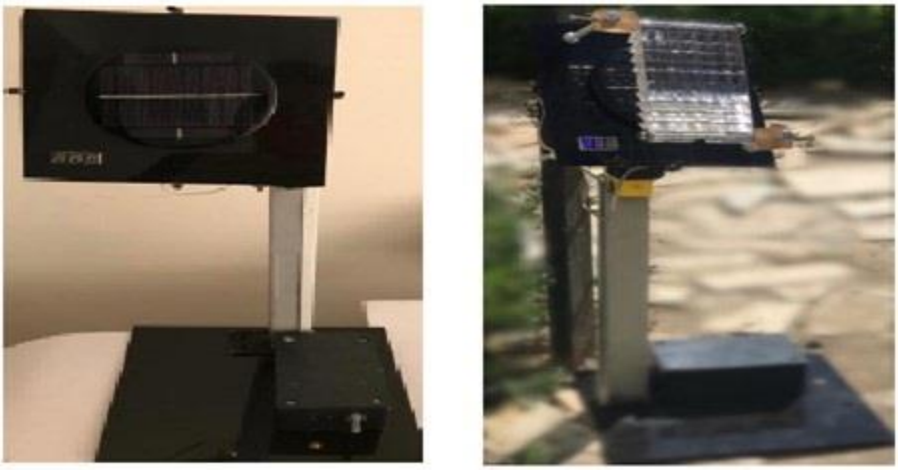
The proposed dual-axis sun tracking system is designed in three units separately. Generally speaking, these three units are named motion trajectory generation, process, and control. The algorithm of the sun trajectory is generated in the first unit which can be used regardless of the geographical positions and time zone. Namely, the processing unit can be run in either continuous or discrete modes. Following this, the controlling unit produces required controlling signals of motors as well as essential signals for system movement in the proper direction. Additionally, a suitable helical DC gear motor (based on the panel weight with specific parameters) along with a motor driver module L289, have been applied for changing the orientation of the panel. Also, a miniature digital voltmeter has been used in the experimental setup with high sensitivity and accuracy. Another point is that, besides the trajectory calculations, detection of light direction has been done with four light-dependent resistors (LDR), in four inverter circuits. The analog outputs of these sensors must be converted to digital ones for microcontroller signal recognition, in order to turn the panel relative to light direction with higher accuracy. The features of the new sun tracking module can be represented as follows:

- Less energy consumption in order to reach maximum efficiency
- Simple mounting and running along with the proper performance and lower cost
- Reliability of the system performance in noisy environments with the wind, dust, rain, and variable temperature
- Modular design and simplicity in different sections of mechanical and electronic units of the system in order to reduce cost, increase the optimal lifetime of the system, ease of troubleshooting, and repair
- Automatic control and precise rotation in order to adjust the PV panel in the proper direction

Hence, the final experimental setup in this study includes a defined dual-axis sun tracking module, four semi-Fresnel lens arrays with 90 cm x 20 cm dimensions (according to the previous study [6]), a PV panel, which is included four striped cells with a width of 2 cm (equal to the width of the focused light strip) and is placed at a distance equal to the focal length of the lens (5 cm). The final results of experimental data have been represented based on data analysis in the originpro9.12 software package.

3. Results and Discussion

The semi-Fresnel convergent structure is designed and constructed from PLEXIGLAS material (as a transparent ambient in front of sunlight) in a previous study in our laboratory[6]. Also, Fig. 3 (a, b) illustrates the new improved dual-axis sun tracking system and experimental setup respectively by applying a semi-Fresnel lens array which is used in this study.



(a) (b)

Fig. 3. a) Improved dual-axis sun tracking system and b) Final experimental setup by applying semi- Fresnel lens array as a convergent structure

A. Results of Simulation

Having looked said above, in the first step, characteristic responses of a 20 µm x 1 µm single monolayer silicon PV Cell were simulated either with or without applied Fresnel lens in the COMSOL Multiphysics environment (in a micro dimension) which were under a standard solar radiation spectrum (AM 1.5) in 40 different wavelengths as a rough spectrum. In fact, finite element calculations in real practical dimensions sometimes are out of system power due to mathematical convergence. To that end, simulation results could be compensated by applying the number and real PV cells size. Characteristic responses of PV cells under applied conditions are shown in Fig. 4 which are included as I-V (green curve) and output power (blue curve) versus applied voltage with a maximum output power of ~11.9 mW likewise fill factor of 0.81 (calculated depending on Eq. (1)).

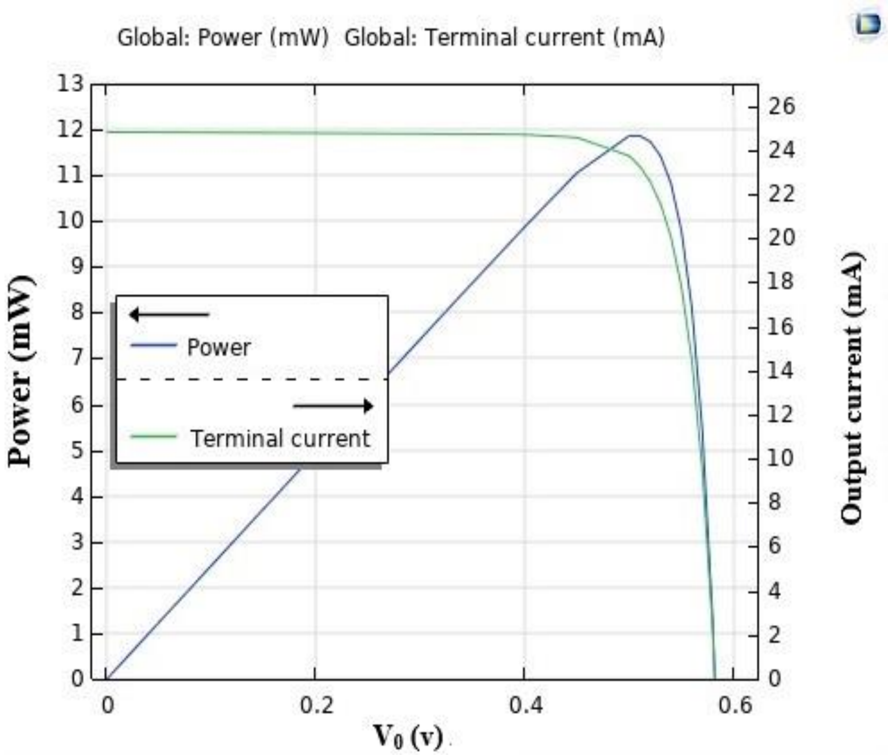


Fig. 4. Characteristic responses of a single monolayer silicon PV Cell under applied condition, I-V curve (green) and output power curve (blue) versus applied voltage.

In the next step, the Fresnel lens as a transparent ambient in front of the sun rays was designed as mentioned above. The sun rays as the electromagnetic wave (for example: in wavelength of 500 nm), after passing through a transparent environment of the lens, are concentrated on a small area in focal point with a high density of flux and energy (Area which is named "A" as illustrated in Fig. 5). Electric field distribution, as a component of the electromagnetic field (wave) in the air gap between point A (cell surface position) and Fresnel lens versus x coordination in specific wavelength (i.e. 500 nm) is illustrated in Fig. 5.

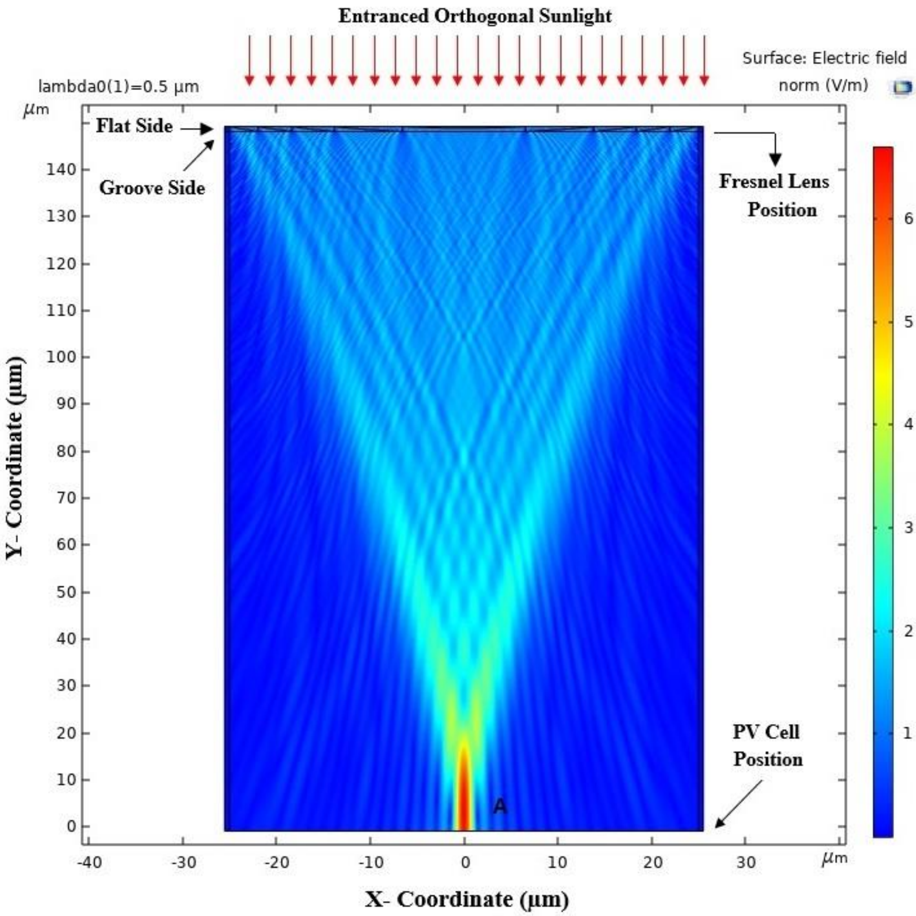


Fig. 5. Distribution of normalized electric field, as a component of the electromagnetic wave in the air gap between focal point "A" and Fresnel lens position

Output power density distribution (averaged in time) in the focal length versus x coordination, is shown in Fig. 6 versus x-coordination (µm) in 8 different selected wavelengths (nm) of normalized entrance electromagnetic field spectrum which is in accordance with the electric field distribution that is reported for (i.e. 500 nm) (as illustrated in Fig. 5).

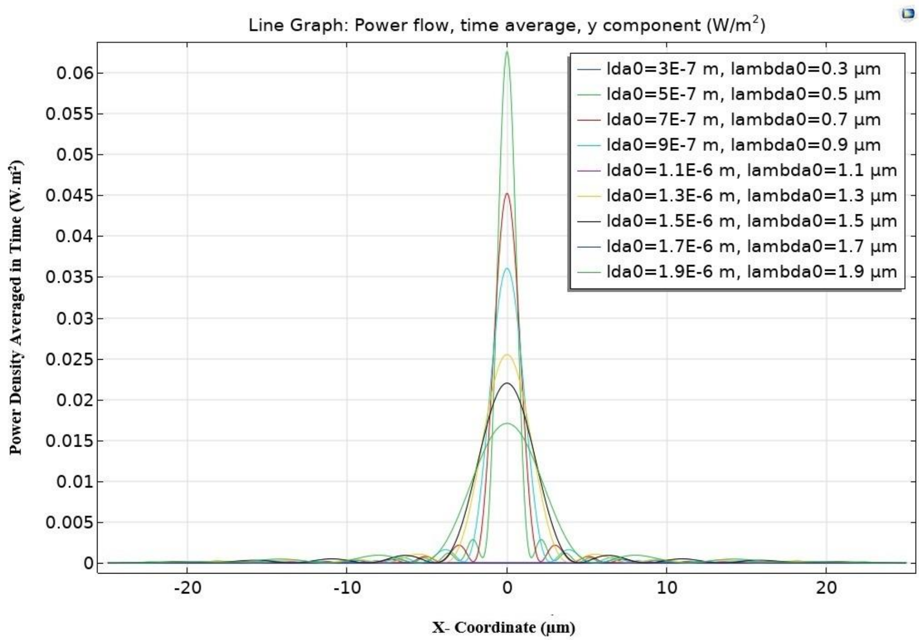


Fig. 6. Power density distribution averaged in time (w/m^2) versus x-coordination (µm) in 8 different selected wavelengths (nm) of normalized entrance electromagnetic field spectrum

According to the results which are revealed in Fig. 5 and Fig. 6, orthogonal sun rays will be refracted based on the reviewed Eq. (3)-(7) and focused on a small area of PV cell in focal length with high energy intensity. The spectral irradiance changes in different 40 selected wavelengths, which are represented in Fig. 7 as a rough solar spectrum, have been given to the same PV cell and characteristic responses of the cell were reevaluated.

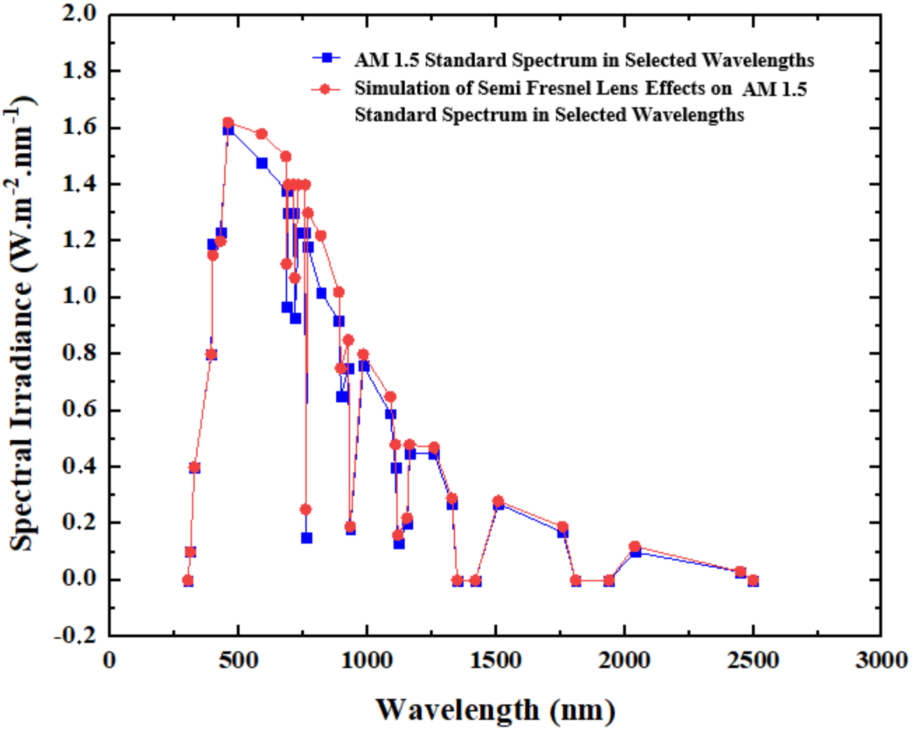


Fig. 7. Spectral irradiance of rough AM 1.5 standard spectrum ($W.m^{-2}.nm^{-1}$) in 40 selected wavelength versus wavelength (nm)

What's more, the semi-Fresnel lens effects on characteristic responses of a monolayer silicon PV cell, in the applied same condition, are shown in Fig. 8, which are included as I-V (green curve) and output power (blue curve) versus applied voltage with a maximum output power of ~19.1 mW and 0.84 fill factor (by using Eq.(2)).

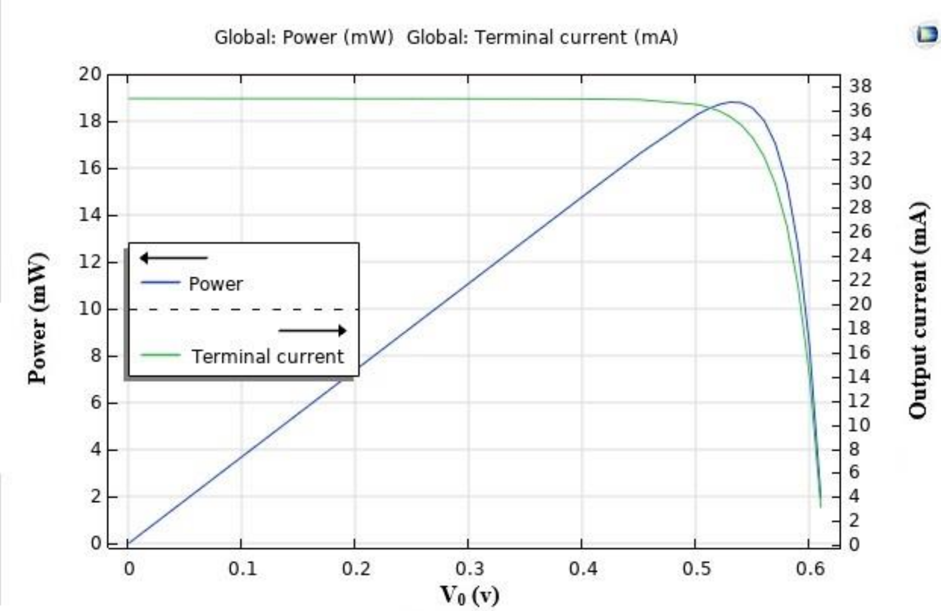


Fig. 8. Characteristic responses of monolayer silicon PV Cell under Fresnel lens I-V (green curve) and output power (blue curve) versus applied voltage.

As you can see, compared to Fig. 4 and Fig. 8, using a Fresnel lens as a convergent structure increase PV cell's output characteristic responses, such as I-V parameters, output power, fill factor (and also efficiency). Furthermore, the results of simulation are verified by previous studies in our laboratory [6].

B. Experimental Results

The dual-axis sun tracking system is designed and constructed to change panel orientation to convert the solar energy efficiently following seasonal changes, day time, longitude and latitude, sunrise and sunset to calculate the height and azimuthal in panel angle regarding the horizon. As mentioned above, the dual-axis sun tracking module merely adjusts the panel perpendicular to sunlight all the time with high accuracy. Along with it, tracking system accuracy has significant effects on a plethora of parameters such as output power and characteristic responses of the PV panel and also the function of the convergent structure. Therefore, control unit angle error is tried to be held near to<±1°. Sun rays concentration make increases the temperature of the system through a semi-Fresnel lens array on a PV panel and consequential side effects on its

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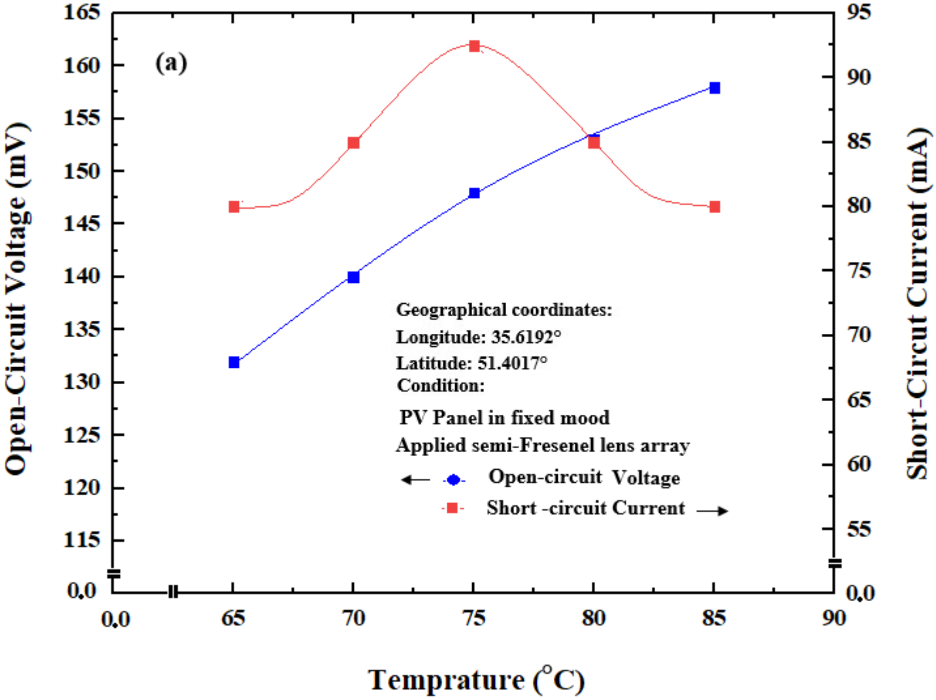
characteristic responses above 75 °C. Fig. 9 (a, b) illustrates output panel characteristic responses as a) short-circuit current (mA) and open-circuit voltage (mV), b) efficiency versus temperature (°C). To this end, it is necessary to control the temperature increment during this study. Incidentally, rays concentration in a narrow strip area is a proper solution instead of a point area, which has been considered in the design steps of the semi-Fresnel lens array. Since this issue could protect the structure from heat generation damages, the area of the cells can be reduced efficiently (equal to the strip of the focused light) also increase efficiency nearby 2.5 or 3 times in comparison with output structure without the semi-Fresnel lens array.



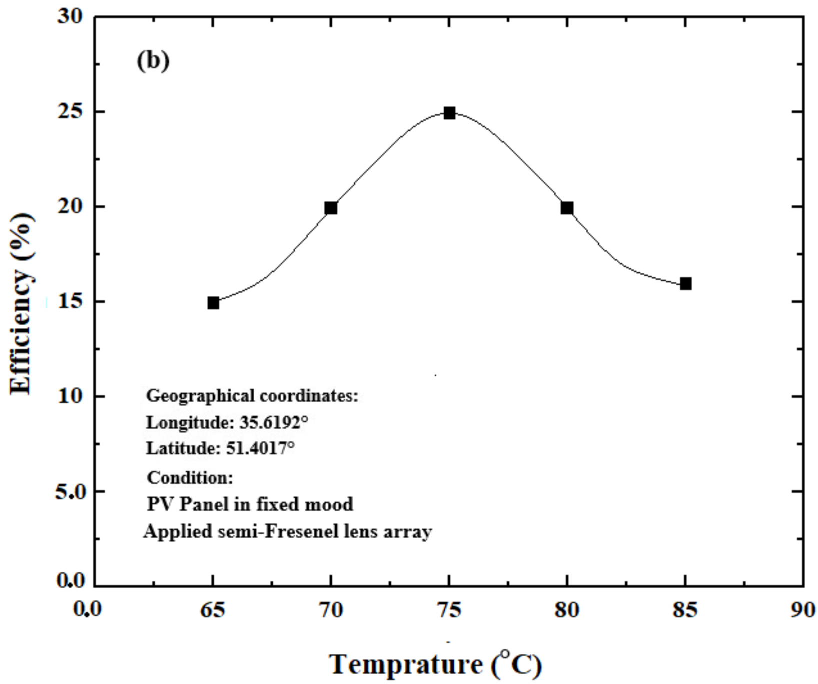


Fig. 9. The output characteristic responses of the panel as a) short-circuit current (mA) and open-circuit voltage (mV), b) efficiency versus temperature (°C).

To illustrate, the PV panel's output power is daily represented in Fig. 10 along with the improved dual-axis sun tracking module either with a semi-Fresnel lens or not. Still, it is essential to hold the PV panel in focal length for the proper performance of the lens. Therefore, using the semi-Fresnel lens array can tremendously improve the output power of the panel, especially at the beginning and the end of the day. Also, TABLE I shows a comparison between the output power of the same PV panel through the semi-Fresnel lens array by applying two types of sun tracking systems includes the new proposed dual-axis sun tracking module and the prototype one (as proposed in [6]) and fixed mood.

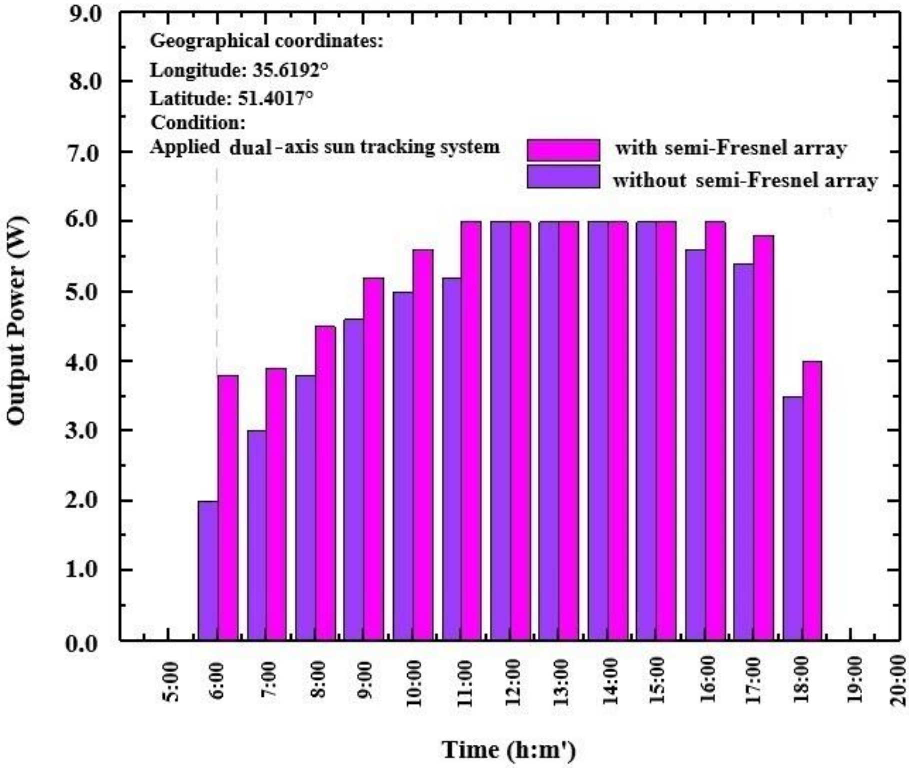


Fig. 10. The output power of PV cell by applying dual-axis sun tracking system with and without Fresnel lens array versus time of day from sunrise to sunset

Looking from an overall perspective, what stands out is that these result demonstrations illustrate that the use of the proposed dual-axis sun tracking system can enable to improve output efficiency and characteristic responses of the PV cell array particularly in output power and current efficiency for a long time in a day toward the previous model. Moreover, change of the panel orientation, which depends on the sun position by the proposed dual-axis sun tracking system, has benefit of sun rays in a day efficiently. Furthermore, concentration on them through the lens make improve the characteristic responses on applied striped cells. All things considered, these improvements seem to reduce the effective area of PV panels as well as their cost especially regarding equipment expenses which increase time efficiency in their performance unexpectedly with a fixed panel.

TABLE I
Comparison of the output power of proposed dual-axis sun tracking system with the prototype one in previous study and fixed panel [6]

Day Time (h:m)	Output Power (W) (This study)	Output Power (W) (Previous study [6])	
	Tracking Mood	Tracking mood	Fixed mood
6:00 AM	3.8	-	-
7:00 AM	3.9	-	-
8:00 AM	4.5	-	-
9:00 AM	5.2	2.8	2.0
10:00 AM	5.6	4.5	3.2
11:00 AM	6.0	5.0	4.1
12:00 AM	6.0	6.0	5.5
1:00 PM	6.0	6.0	5.5
2:00 PM	6.0	5.0	4.2
3:00 PM	6.0	-	-
4:00 PM	6.0	-	-
5:00 PM	5.8	-	-
6:00 PM	4.0	-	-

[a] W as a unit of output power (Watt).

4. CONCLUSION

In order to optimize characteristic responses of PV cells per unit of cost and effective area, the Fresnel lens array was applied as a convergent structure. Results of simulation of Fresnel lens effect on output characteristic responses of PV cells show good improvement which is in good agreement with experimental data. As a semi-Fresnel lens concentrates on orthogonal entrance sun rays in a small area of PV cells while other rays are considered as a loss. Consequently, the design and construction of a proposed dual-axis sun tracking system can play a crucial role in PV cells output characteristics improvement together with the use of solar radiation efficiency.

As cited above, the sun tracking system adjusts the PV panel (or the flat side of the Fresnel lens) in the proper orientation (perpendicular to the sunlight) by generating a trajectory of panel movement to use sunlight efficiently all day long. Thus, the proposed dual-axis sun tracking systems along with applying semi-Fresnel lens array as a convergent structure undoubtedly cause to improve output characteristic responses in the unit of the effective area of PV cells and their cost by considering the costs of equipment in comparison with fixed mood. On the other hand, the time of the PV cells efficient performance will be extended longer from sunrise to sunset regardless of location, time zone. Based on the promising results presented in this paper, the rest of the issues will continue to be addressed and presented in future papers.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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