LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2024, N 5

DOI: 10.2478/lpts-2024-0039

MODELLING Π-SHAPED CONCENTRATING OPTICS FOR LCPV SOLAR CELLS USING FRESNEL LENS

A. Kapparova, S. Orynbassar, G. Dosymbetova*, D. Almen,
E. Yershov, A. Saymbetov, M. Nurgaliyev, N. Algazin,
A. Sharipbay, D. Zhastalapova

Faculty of Physics and Technology,
Al-Farabi Kazakh National University,
71 Al-Farabi, Almaty 050040, KAZAKHSTAN
*e-mail: dossymbetova.g@kaznu.kz

Most concentrating optics do not show good performance at higher incidence angles and have low acceptance angles and, therefore, they require a high-accuracy solar tracking system, which is costly. In this study, by detailed investigation of optics of the proposed Π-shaped concentrating optics, it was found that system remained high in terms of optical efficiency and its concentration ratio at certain higher incidence angles. During the work, ray path through the concentrating optics, width of the light spot at different incidence angles were calculated. Optical efficiency, geometrical concentration ratio, concentration ratio at different incidence angles were found by the results of COMSOL Multiphysics calculations. It was found that the system had a high optical efficiency of approximately 95% and its concentration ratio of 3x-5x was at the range of ±0-20 degrees of incidence angle, and it could reduce the work of a solar tracking system. As well, an increase in the optical efficiency could be seen from 0 to 5 degrees of the incidence angle and an increase in the concentration ratio could be seen from 0 to 12 degrees of the incidence angle in terms of the reflective mirrors which helped redirect the rays to the solar cells. Optical systems with such a high incidence angle could reduce the performance of the solar tracker system, and it reduced the overall cost and energy consumption of the LCPV.

Keywords: *Concentration ratio, Fresnel lens, incidence angles, light spot, optical efficiency, ray path, Π-shaped.*

1. INTRODUCTION

These days humanity consumes the energy generated by the sources, which pollute the environment. In one year, humanity consumes the energy, which the Sun delivers to Earth in 1 hour [1]. It means we are losing the clean, free energy; therefore, improving performance of solar power plants is a significant task. Researchers demonstrated that the substantial and readily available solar energy can effectively meet global energy demands [2], [3]. Nowadays, the amount of energy generated by solar panels is not sufficient, and electrical efficiency of the systems are lower. There are some opportunities to improve the performance of solar batteries. Using high-efficient solar cells, for example, multi-junction solar cells, is one of the ways to tackle the issue, but these kinds of solar cells are expensive, and their manufacturing process is complex [4]–[6].

Another way to improve the performance of generating electrical energy of photovoltaic systems is increasing the incident solar radiation power [7], [8]. The output power of solar batteries depends on the power of solar radiation; therefore, by increasing the incident solar radiation, it is possible to increase the generated power. Those systems are called concentrating photovoltaics (CPV). In CPV systems, by using more affordable mirrors and/or lenses, the overall cost can be reduced [9]. The paper [10] proved that average power output increased considerably using mirrors. Another work [11] improved the maximum power of the solar panel by 17 % by using flat mirrors. Currently, the CPV systems use different types of concentrating optics and depending on their performance they are classified as follows: LCPV (>10 suns) [12], MCPV (10–100 suns) [13], HCPV (100–2000 suns) [14] and UHCPV (42 000 suns) [15]. LCPV and MCPV systems have basic design principles even though their concentration ratio is lower [16]. HCPV systems usually consist of expensive high-efficiency small solar cells and several optical elements [17]. Even though HCPV systems have a high concentration ratio, the installation and maintenance are complex and cost-ineffective.

Among the CPV systems, LCPV modules are particularly appealing, since they can be affordable due to lowered active material usage, a Balance-Of-the-System cost potentially equivalent to that of standard fixed panels [18]. In the mid-2000s, Low Concentration Photovoltaics (LCPVs) made their market debut. LCPVs are still continuing their significance in the solar technology landscape compared to traditional flat PV panels [19]. Another benefit of LCPV systems is that they can be used with cheap commercial silicon solar cells, which help reduce the overall cost of the system. The paper [20] compared poly-crystalline and mono-crystalline silicon solar cells under low concentration ratio and concluded that poly-crystalline PV module was more efficient than mono-crystalline under LCPV conditions despite of the mono-Si PV module having higher performance compared to poly-Si PV module under STC.

The most common and widely adopted concentrating optics are the Fresnel lens and parabolic mirror [21]. Types of concentrating optics for LCPV systems are compound parabolic concentrators (CPCs) and planar flat concentrators or V-Trough, ACPC, parabolic concentrator, cylindrical troughs, linear Fresnel reflectors [22]. The work [23] could increase the output power of CPV using CPC by 3 times compared to a non-concentrating system. Another work was performed using commercially available monocrystalline silicon photovoltaic solar cells and compound parabolic concentrator, and a concentration ratio of the LCPV reached 7x and the CPC optical efficiency was 55 % [24]. The work [25] examined a reflective asymmetrical compound parabolic concentrator (ACPC), which increased the power concentration ratio of the panel by 2.1 times compared to a similar non-concentrating panel. Another common type of LCPV and MCPV optics is linear Fresnel lenses, which can reach 5x concentration ratio but they are usually used with solar/thermal systems [26].

The Fresnel lens can be a linear Fresnel lens or a point focus Fresnel lens which is just called Fresnel lens [27]. Plastic Fresnel lenses are the most common primary optical concentrator since they are light-weight and capable of elevating the density of solar energy and possess advantages of compactness, simplicity in manufacture, and relative cheapness [28].

The work [29] designed a Fresnel lens which had a shorter focal length, the acceptance angle of the whole system was between 0.6 to 0.8°, and the optical efficiency obtained by simulations was between 80 to 90 %. To increase the acceptance angle and uniform distribution of sunlight, secondary optical concentrators were used [30].

Authors [31] compared two secondary optics: the CPC and the cone for Fresnel lens-based concentrator. Even though the concentration ratio increased in the case of the cone, the concentration was higher in the case of the CPC when the angle of incidence increased. Fresnel lens was used as a primary optical element with four types of secondary optics to get wider acceptance angle in [32]. As it can be seen, the above-mentioned Fresnel lens-based concentrating photovoltaics have a low acceptance angle because they have a 1000x concentration ratio. Only high-efficiency small multi-junction solar cells can resist high concentrations. However, such solar cells are multiple times more expensive than single-junction silicon solar cells.

The work [33] showed that when using Fresnel lens as a concentrator for polycrystalline solar cells, it is possible to get an LCPV system, which can generate 27 % more energy than a non-concentrated silicon solar cell. The work [34] investigated different Fresnel lens designs and determined their optical efficiency. The design of the concentrating optics and the distance between solar cell and lens has a significant impact on the optical efficiency, which is defined as how efficiently the photons of the incoming radiation are transferred to the solar cell [35].

Point-focusing lenses need to operate in normal incidence, which means the incidence angle is zero, with accurate sun tracking in order to work properly [36]. A solar tracker is an essential component of CPV with such types of concentrators. The solar tracker can increase the PV panel energy by approximately 33 % [37]. However, a substantial amount of energy is consumed by solar tracking systems [38], [39]. Subsequently, when using point-focus Fresnel lenses, there has to be additional optics which helps obtain angled rays and increase the acceptance angle. The acceptance angle or optical tolerance for parabolic dishes and Fresnel lenses, without additional optics can be expected to be very low ±0.5 or less [40], [41]. If rays hit the solar cell with a greater angle than the acceptance angle, then non-uniform irradiance distribution may occur. To tackle the issue, a secondary optical element is added to the CPV system [42]. The secondary optical element helps not only to improve the uniformity of irradiance distribution, but also increases the sunlight tracking tolerance [43]. The paper [39] shows that the tracking tolerance of the dome-shaped non-imaging Fresnel lens held efficiencies of 90 % up to an incident angle of 0.4°, then dropped to 80 % at 0.6° and then to 10 % at 1°. It means, when using Fresnel lenses as a concentrator, an accurate solar tracking system is necessary. However, the solar tracking systems consume more electrical energy to move the whole system [44]–[46]. Reducing the work of solar tracking is usually done by designing optical systems which redirect the sunlight to the solar cell. Therefore, it is important to design Fresnel based concentrators with additional optics.

The aim of the study is to design an optical system which can help reduce the work of solar tracking systems and increase the acceptance angle while not reducing the optical concentration ratio. In this work, we added reflective surfaces perpendicularly on the edges of Fresnel lens which helped redirect the inclined rays to the solar cell at higher incidence angles. The proposed optical system is called Π-shaped concentrating optical system. The novelty of the work is a mathematical model of Π-shaped concentrating optics and widening the incidence angle of a Fresnel lens-based LCPV with polycrystalline silicon solar cells. The proposed Π-shaped LCPV with nine polycrystalline solar cells showed good performance at higher incidence angles. Moreover, using cheap silicon solar cells and simple, affordable optics can reduce the system cost. As the system which has a wide incidence angle, it can simplify the work of a solar tracking system and reduce its power consumption.

2. MATHEMATICAL MODEL OF Π-SHAPED CONCENTRATING OPTICAL SYSTEM

A Fresnel lens is one of the types of optical lens, and it consists of a series of concentric grooves. The grooves allow the lens to achieve the same optical efficiency as a traditional lens but it is much thinner and lighter. It is known that the Fresnel lens concentrates the sunlight to one point, but if the polycrystalline solar cell is placed at the exact focus of the lens, the light does not cover the entire surface of the solar cell. Due to the concentrated light on the centre of the solar cell, it leads to a hot spot and the failure of the solar cell. Therefore, it is necessary to place the lens at such a distance that it evenly and completely covers the surface of the solar cell (Fig. 1a). However, placing the photocell at the focus of the Fresnel lens does not eliminate the need for a solar tracking system. Therefore, nine solar cells, which can increase the incidence angle of the light entering the Fresnel lens (Figure 1b), are used in our proposed Π-shaped optical system. However, the light deviates from the surface of the solar cell at a certain value (Fig. 1c). To solve this problem, mirrors can be placed around the distance between the Fresnel lens and the photocells, as shown in Fig. 1d.

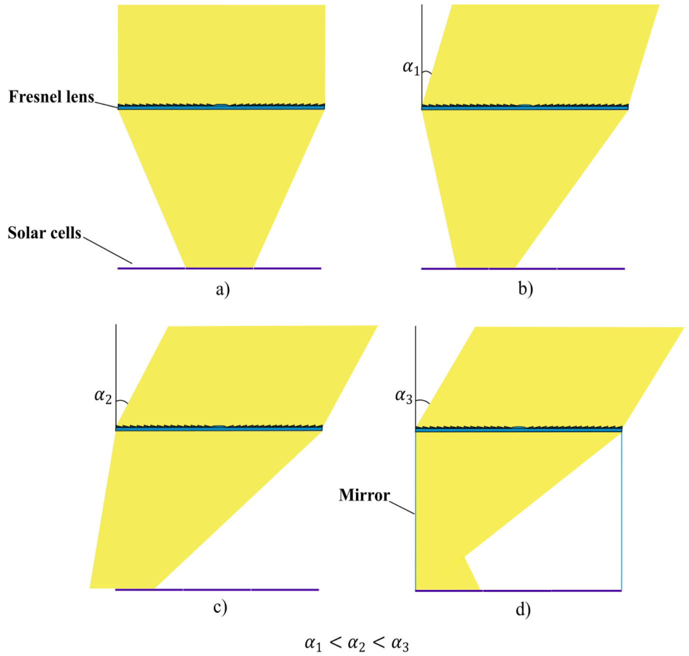

Fig. 1. П-shaped concentrating optics at different incidence angles.

As shown in Fig. 2, the П-shaped concentrating optics consists of a Fresnel lens, four reflective mirrors, which make the concentrating system as a letter П, and nine polycrystalline silicon solar cells. The length of each solar cell is 50 mm, length of Fresnel lens is 150 mm, height of the mirror is 150 mm.

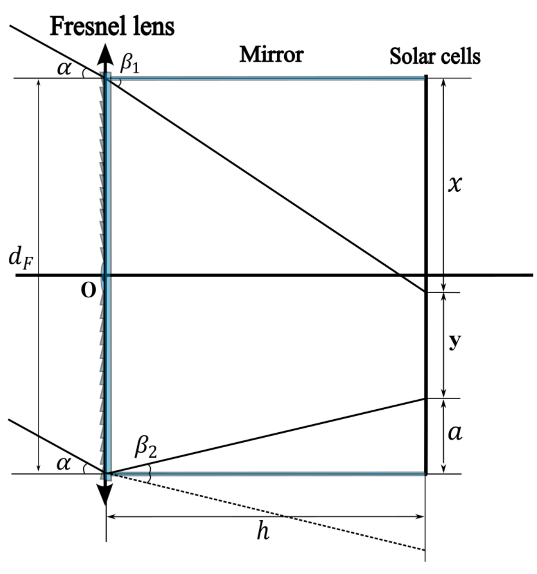

Fig. 2. The geometrical diagram of П-shaped concentrating optics.

Figure 2 shows the path of the ray at a certain angle on Π-shaped optical system based on a Fresnel lens. Considering the cross-section of the Fresnel lens and assuming that it is a system consisting of prisms, and dividing it into two halves symmetrically, the ray paths corresponding to both right and left sides of the lens are calculated using Eqs. (1)–(4). The light passing through the Fresnel lens refracts at a certain angle and falls on the surface of the solar cell. Accordingly, the position of the incident beam is determined by the following equations:

$$tan\,\beta_1 = \frac{x}{h}; \tag{1}$$

$$x = h \cdot tan\,\beta_1, \tag{2}$$

where β_1 is refracting angle, x is the position of the right incident beam.

The ray path for the second part of the Fresnel lens is calculated by Eqs. (3) and (4). The light passing through the lens is refracted at a certain angle and reflects off the mirror and falls on the surface of the solar cell.

$$tan\beta_2 = \frac{a}{h}; \tag{3}$$

$$a = h \cdot tan\beta_2, \tag{4}$$

where β_2 is refracting angle, a is the position of the left incident beam.

We consider the rays calculated by these two equations to be the outermost rays. Assuming that all the remaining rays are located between these two rays, we can calculate the length of the light spot with the following equation:

$$y = d_F - (a + x), \tag{5}$$

where y is the length of the light spot.

The next problem is to determine at what angle the ray passing through the Fresnel lens is refracted. We consider the lens as a system consisting of prisms as shown in Fig. 3. It is necessary to determine the angle of refraction by calculating the ray path through the prism.

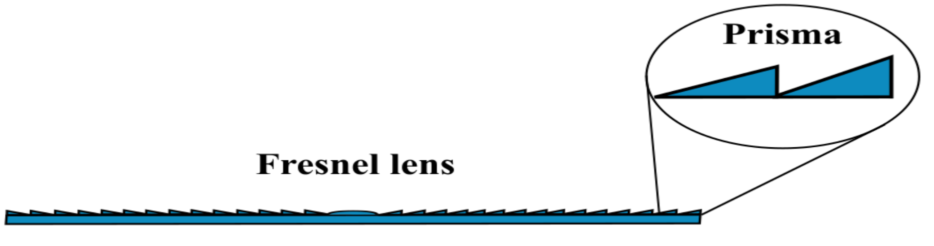

Fig. 3. Fresnel lens structure.

Prisms should be considered in two different cases depending on their location on the two right and left sides from the centre of the Fresnel lens. In the first case, let us consider the prism located on the right side of the Fresnel lens.

First of all, we express the incidence angle of the ray α for the horizontal plane:

$$\alpha = \alpha_1 - \psi\,, \tag{6}$$

where α_1 is the angle between incident ray and perpendicular on prism, ψ is the deflection angle of the prism.

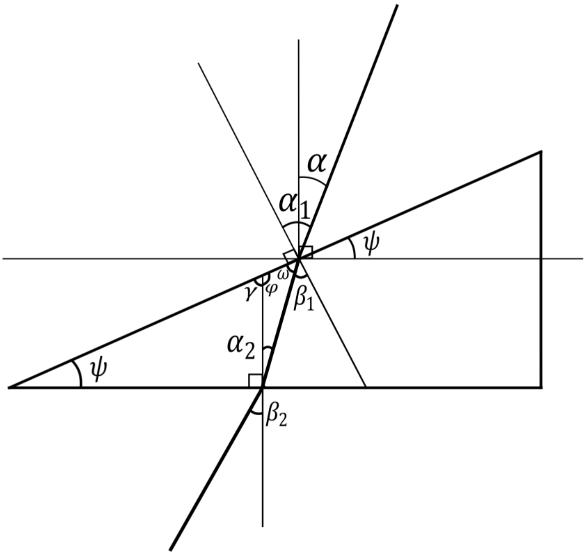

Fig. 4. Path of the rays through right prism of Fresnel lens grooves.

According to Snell's law, the angles α_1 and β_1 can be found as follows:

$$\frac{sin\alpha_1}{sin\beta_1} = \frac{n}{1}; \quad (7)$$

$$n \cdot sin\beta_1 = sin\alpha_1; \quad (8)$$

$$sin\beta_1 = \frac{sin\alpha_1}{n}, \quad (9)$$

where n is a refractive index.

Considering the Eqs. (7)–(9), the angle can be determined as follows:

$$\beta_1 = arcsin\left(\frac{sin\alpha_1}{n}\right). \quad (10)$$

Subsequently, α_2 can be expressed with angles β_1 and ψ:

$$\omega = 90° - \beta_1$$

$$\gamma = 180° - 90° - \psi$$

$$\varphi = 180° - \gamma$$

$$\alpha_2 = 180° - \varphi - \omega$$

$$\alpha_2 = 180° - (90° + \psi) - (90° - \beta_1)$$

$$\alpha_2 = \beta_1 - \psi; \quad (16)$$

$$\frac{sin\alpha_2}{sin\beta_2} = \frac{1}{n}; \quad (17)$$

$$sin\beta_2 = n \cdot sin\alpha_2. \quad (18)$$

The refraction angles of the ray coming out of the prism can be determined using the following equations:

$$sin\beta_2 = n \cdot sin\,(\beta_1 - \psi); \quad (19)$$

$$sin\beta_2 = n \cdot sin\,\left(arcsin\left(\frac{sin\alpha_1}{n}\right) - \psi\right); \quad (20)$$

$$\alpha_1 = \alpha + \psi; \quad (21)$$

$$sin\,\beta_2 = n \cdot sin\,\left(arcsin\frac{sinsin(\alpha+\psi)}{n} - \psi\right); \quad (22)$$

$$\beta_1 = arcsin\left(n \cdot sin\,\left(arcsin\frac{sinsin\,(\alpha+\psi)}{n} - \psi\right)\right). \quad (23)$$

Next, we need to determine the ray path for the prism on the left side of the Fresnel lens. The calculations for the left side of the lens will be as the right side.

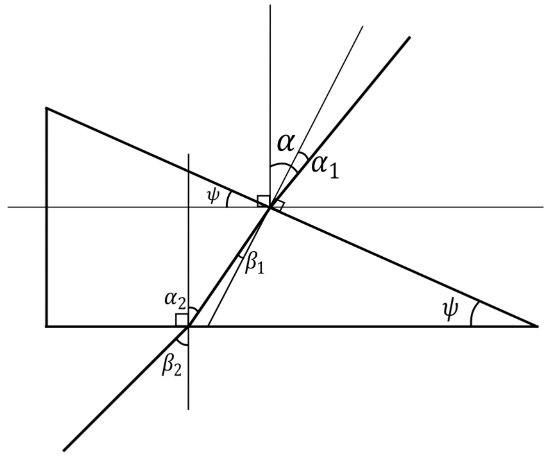

Fig. 5. Path of the rays through left prism of Fresnel lens grooves.

First of all, we express the incidence angle of the ray for the horizontal plane:

$$\alpha = \alpha_1 + \psi. \quad (24)$$

Further, we calculate the path of the incident ray at a certain angle and determine the angle of refraction using the following equations:

$$sin\,\beta_2' = n \cdot sin\,\left(arcsin\frac{\sin(\alpha-\psi)}{n} + \psi\right); \quad (25)$$

$$\beta_2{}' = arcsin\left(n \cdot sin\,\left(arcsin\frac{sin\,(\alpha-\psi)}{n} + \psi\right)\right). \quad (26)$$

According to the calculations of the П-shaped optical system, the dependence of the width of the light spot on the surface of the solar cells on different incidence angles was established. In order to compare the obtained results, a 3D model of the П-shaped optical system was created in the COMSOL Multiphysics program, and a Ray Tracing simulation was carried out using the Geometrical Optics section of the program.

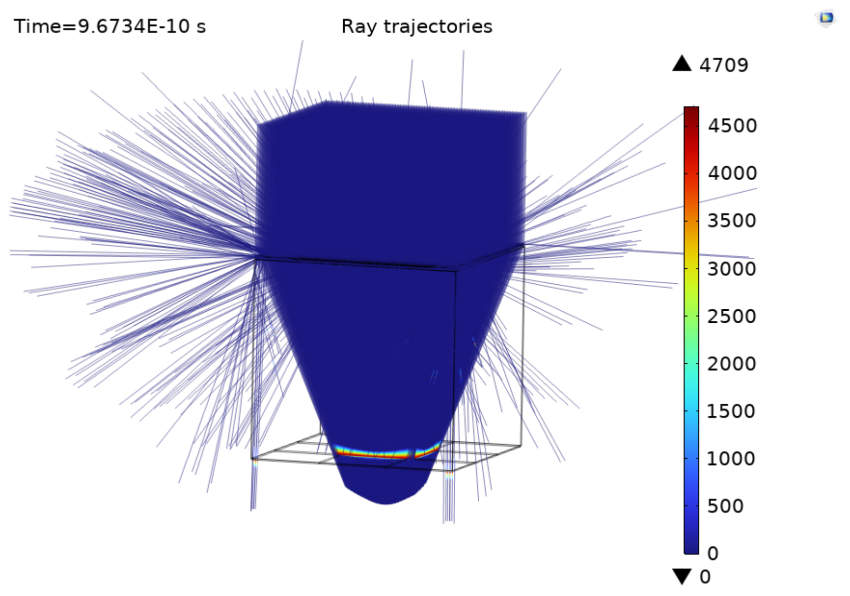

Fig. 6. Ray tracing simulation of the П-shaped optical system.

As a result of the simulation, we determined the total number of rays that hit each solar cell by setting the ray detector state. If the initial number of rays is known, then we can determine the optical efficiency using the following equation:

$$\eta_{opt} = \frac{n_{entry}}{n_{exit}} \cdot 100\% \, , \qquad (27)$$

where n_{entry} is the number of rays falling on the surface of the solar cell, n_{exit} is the number of primary rays, which equals 5700, in our case.

Optical efficiency is one of the most significant parameters in the design of solar concentrators. During the simulation, the sunlight falls on the П-shaped optical system at an incidence angle of 0–25 degrees. As a result, the dependence of the optical efficiency on different incidence angles was obtained.

3. RESULTS OF THE CALCULATIONS AND MODELLING THE П-SHAPED OPTICAL SYSTEM

We can determine the length of the light spot at different incidence angles using Eq. (5). We can see the dependence of the width of the light spot on the incidence angles from 0 to 20 degrees in Fig. 7. Taking into account that the width of the light spot should not be smaller than the length of the solar cell, i.e., 50 mm, we determined that the deviation of 18 degrees of incidence angle is the limit value. If the incidence angle exceeds 18 degrees, the length of the light spot decreases.

The fact that the width of the light spot is smaller than the length of the solar cell leads to a decrease in optical efficiency, which is one of the important parameters in concentrating optical systems. The high value of the optical efficiency in variations of the incidence angle allows reducing the operation of the solar tracking system.

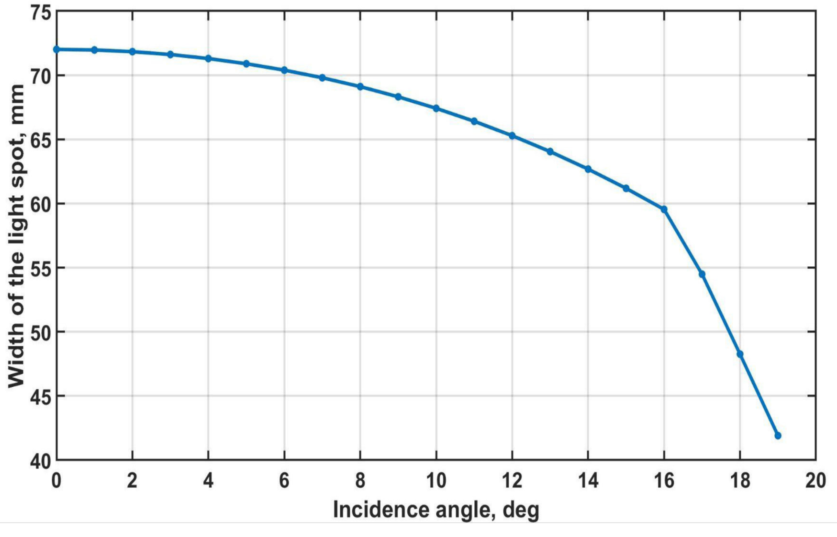

Fig. 7. Width of the light spot at different incidence angles.

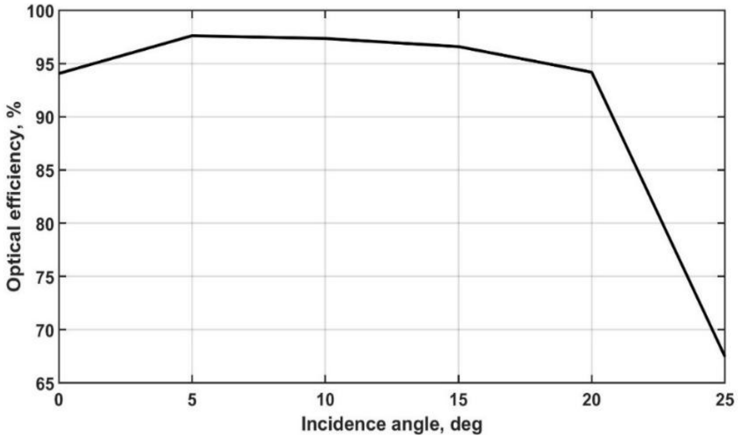

Fig. 8. Optical efficiency at different incidence angles.

Figure 8 shows the dependence of the optical efficiency of the system on different incidence angles using the results obtained on COMSOL Multiphysics. From this dependence shown in Fig. 8, we can see that the value of the optical efficiency decreases when incidence angle exceeds 20 degrees. If we do not make any changes to the geometry of the optical system, it can be stated that the efficiency of the optical system is directly proportional to the width of the light spot. The optical efficiency rises from 94 % to 97 %, when the incidence angle expands from 0 to 5 degrees, and this is the significant benefit of the system. We can see that the dependence constructed as a result of the calculations shown in Fig. 7 is similar to the dependence obtained from the simulation in Fig. 8.

One of the important optical parameters of optical systems is the geometric concentration ratio, which is determined as the ratio of the lens area to the cell area:

$$C_g = \frac{A_{lens}}{A_{cell}}, \tag{28}$$

where A_{lens} is the area of the Fresnel lens, A_{cell} is the area of the solar cell.

Depending on the equations used in the description of the П-shaped optical system, the geometric concentration ratio can be determined as follows:

$$C_g = \left(\frac{d_F}{y}\right)^2. \tag{29}$$

Using Eq. (29), the geometric concentration ratio of the П-shaped optical system is calculated, and the dependence of the geometrical concentration ratio on the incidence angle is plotted in Fig. 9.

If we consider that the d_F is the constant value, y is the width of the light spot, the geometrical concentration ratio only depends on the width of the light spot. Narrowing the width of the light spot leads to increasing the geometrical concentration ratio. It can be seen in Fig. 9 that the geometrical concentration ratio increases by increasing the incidence angle. By multiplying the geometrical concentration ratio by optical efficiency of the system, we get a concentration ratio of the optical system [47]:

$$C = C_g \cdot \eta_{op}, \tag{30}$$

where η_{op} – optical efficiency. As a result of the calculation, we get the dependence of concentration ratio on the incidence angle shown in Fig. 10.

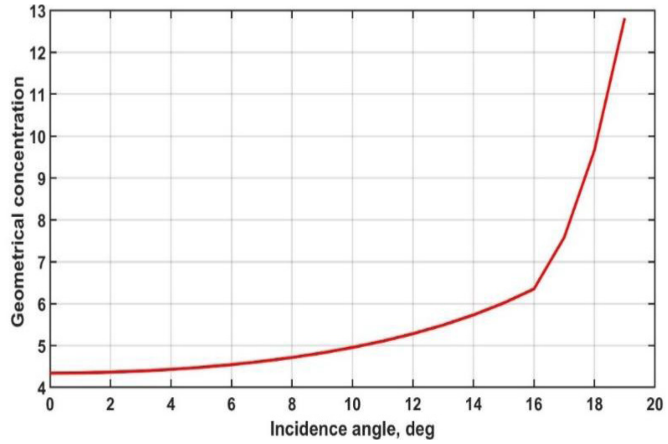

Fig. 9. Geometrical concentration ratio at different incidence angles.

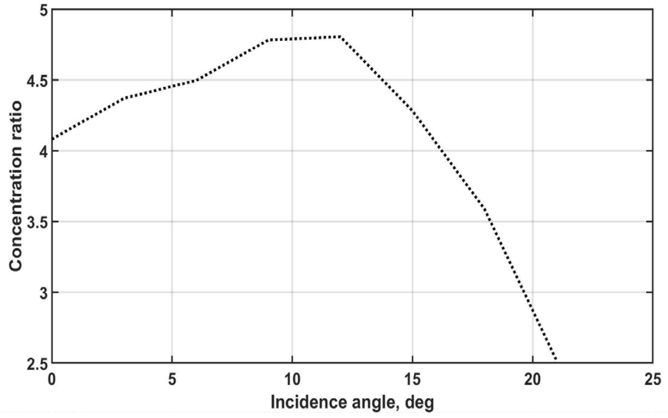

Fig. 10. Concentration ratio at different incidence angles.

As it can be seen in Fig. 10, the concentration ratio decreases by increasing the incidence angle. However, it remains in the range approximately 3x–5x from 0 to 20 degrees of the incidence angle; it shows that the system can exhibit good performance at 20 degrees of the incidence angle, and it benefits to reduce the work of a solar tracking system. In terms of the increase of optical efficiency using reflective mirrors which help redirect the sunlight to the surface of the solar cells, when the incidence angle increases from 0 to 12 degrees, the concentration ratio also increases. Taking into account that the incidence angle deviates from the central normal of the optical surface on both sides, if we double the value of the incidence angle, the optical system maintains high optical efficiency when the sun rotates by 40 degrees.

4. DISCUSSION OF THE RESULTS

During the work, a *П*-shaped optical system based on a Fresnel lens was proposed for low concentrating photovoltaic systems. In order to determine the optical efficiency of the proposed system, geometrical and mathematical calculations were carried out, during the calculation, the width of the concentrated light spot in the *П*-shaped optical system was mathematically expressed, and the length of the light spot was determined. In addition, the change in the width of the light spot at different angles of incidence of light was observed. Based on the calculations, a 3D model of the *П*-shaped optical system was created in the COMSOL Multiphysics software, and its optical efficiency was determined using Ray tracing simulation. Based on the work done, the following results were achieved:

1. The light spot maintained its effective width up to 18 degrees at the incidence angle between 0–20 degrees;
2. When the incidence angle of the optical system was in the range of 0–25 degrees, the optical efficiency did not fall below 95 % up to 20 degrees;
3. The width of concentrated sunlight and optical efficiency were directly proportional quantities;
4. The geometric concentration ratio of the *П*-shaped optical system in the range of 0–20 degrees was calculated using the width of the light spot. As a result, it was determined that the geometrical concentration ratio was about 4–9 at the incidence angle up to 18 degrees;
5. Using the optical efficiency and geometric concentration ratio, the concentration ratio in the range of 0–25 degrees of incidence angle was calculated; as a result, it was determined that the concentration ratio was in the range of 2.5–5 up to 20 degrees, which corresponded to the low concentrating photovoltaic;
6. Using the proposed *П*-shaped optical system, the solar tracker of the LCPV could stand still up to 40 degrees.

Most of the Fresnel lens-based concentrating optical elements or systems have low acceptance angles, and they require high-precision solar tracking systems. Particularly, high concentrating solar cells with Fresnel lens usually have a low acceptance angle. The work [29] designed a Fresnel lens, and its acceptance angle was between 0.6 to 0.8°, and the optical efficiency was between 80 and 90 %. The studies [40], [41], [30] showed that Fresnel lenses with a secondary optics could increase the acceptance angle and uniform distribution of sunlight, but those systems still had comparably low acceptance because those systems provided high concentrated solar radiation, which required small high-efficiency multi-junction solar cells. Due to the small size of the solar cells, concentrating the sunlight into one point becomes more difficult if the rays are not perpendicular to the surface of the lens. In this work, we used inexpensive polycrystalline silicon solar cells as in our one of the previous works [33], it was proven that a polycrystalline silicon solar cell with Fresnel lens at optimal cell-lens distance could generate 27 % more energy than a non-concentrating solar cell. The proposed *П*-shaped optical system allows the LCPV to work without sun tracking up to 20 degrees. In addition, we can even see the increase in the optical efficiency and concentration ratio at lower incidence angles.

In the case of using the proposed optical system, it is possible to provide a low concentration level on the surface of the solar cell. Based on the obtained results, the capability of the proposed ***П***-shaped optical system, which can minimise the operation of the solar tracking system for low-concentration photovoltaic systems, was demonstrated using mathematical calculations and computer simulations.

5. CONCLUSION

Detailed investigation of geometrical optics of the proposed Π-shaped concentrating optics was performed. Expressions describing the incidence ray path through the concentrating optics were presented, and width of the light spot at different incidence angles was calculated. Optical efficiency at different incidence angles was found by the results of COMSOL Multiphysics and geometrical concentration ratio, the concentration ratio was calculated. It was found that the system had high optical efficiency of approximately 95 %, and its concentration ratio of 3x–5x at the range of ± 0-20 degrees of incidence angle and it could reduce the work of a solar tracking system. Additionally, an increase in the optical efficiency can be seen from 0 to 5 degrees of the incidence angle and an increase in the concentration ratio can be seen from 0 to 12 degrees of the incidence angle in terms of the reflective mirrors, which help redirect the rays to the solar cells. Optical systems with such a high incidence angle can reduce the performance of the solar tracker system, and it reduces the overall cost and energy consumption of the LCPV. It greatly simplifies the process of system implementation and maintenance.

ACKNOWLEDGEMENTS

This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19574454).

REFERENCES

1. Lewis, N. S., & Nocera, D. G. (2006). Powering the Planet: Chemical Challenges in Solar Energy Utilization. *Proceedings of the National Academy of Sciences*, *103* (43), 15729–15735. https://doi.org/10.1073/pnas.0603395103
2. Kannan, N., & Vakeesan, D. (2016). Solar Energy for Future World: A Review. *Renewable and Sustainable Energy Reviews*, *62*, 1092–1105. https://doi.org/10.1016/j.rser.2016.05.022
3. Jatoi, A. R., Samo, S. R., & Jakhrani, A. Q. (2021). Performance Evaluation of Various Photovoltaic Module Technologies at Nawabshah Pakistan. *International Journal of Renewable Energy Development*, *10* (1), 97. https://doi.org/10.14710/ijred.2021.32352
4. Yamaguchi, M. (2003). III–V Compound Multi-Junction Solar Cells: Present and Future. *Solar energy materials and solar cells*, *75* (1–2), 261–269. https://doi.org/10.1016/S0927-0248(02)00168-X
5. Klugmann-Radziemska, E. (2023). Environmental Assessment of Solar Cell Materials. *Ecological Chemistry and Engineering S*, *30* (1), 23–35. https://doi.org/10.2478/eces-2023-0002
6. Kafui, A. D., Seres, I., & Farkas, I. (2019). Efficiency Comparison of Different Photovoltaic Modules. *Acta Technologica Agriculturae*, *22* (1), 5–11. https://doi.org/10.2478/ata-2019-0002
7. Michael, J. J., Iqbal, S. M., Iniyan, S., & Goic, R. (2018). Enhanced Electrical Performance in a Solar Photovoltaic Module Using V-Trough Concentrators. *Energy*, *148*, 605–613. https://doi.org/10.1016/j.energy.2018.01.101

8. Al-Ghezi, M. K., Ahmed, R. T., & Chaichan, M. T. (2022). The Influence of Temperature and Irradiance on Performance of the Photovoltaic Panel in the Middle of Iraq. *International Journal of Renewable Energy Development*, *11* (2), 501. https://doi.org/10.14710/ijred.2022.43713
9. Finot, M., & MacDonald, B. (2011). Significant Cost Reduction through New Optical, Thermal, and Structural Design for a Medium-CPV System. *High and Low Concentrator Systems for Solar Electric Applications VI,* 8108, 86–95. SPIE. https://doi.org/10.1117/12.894187
10. Bilal, M., Arbab, M. N., Afridi, M. Z. U. A., & Khattak, A. (2016). Increasing the Output Power and Efficiency of Solar Panel by Using Concentrator Photovoltaics (CPV). *International Journal of Engineering Works*, *3* (12), 98–102.
11. Zainulabdeen, F. S., Al-Hamdani, A. H., Karam, G. S., & Ali, J. H. (2019). Improving the Performance Efficiency of Solar Panel by Using Flat Mirror Concentrator. *AIP Conference Proceedings*, *2190* (1). AIP Publishing. https://doi.org/10.1063/1.5138540
12. Parupudi, R. V., Singh, H., & Kolokotroni, M. (2020). Low Concentrating Photovoltaics (LCPV) for Buildings and their Performance Analyses. *Applied Energy*, *279*, 115839. https://doi.org/10.1016/j.apenergy.2020.115839
13. Hasan, A., Sarwar, J., & Shah, A. H. (2018). Concentrated Photovoltaic: A Review of Thermal Aspects, Challenges and Opportunities. *Renewable and Sustainable Energy Reviews*, *94*, 835–852. https://doi.org/10.1016/j.rser.2018.06.014
14. Maka, A. O., & O’Donovan, T. S. (2020). A Review of Thermal Load and Performance Characterisation of a High Concentrating Photovoltaic (HCPV) Solar Receiver Assembly. *Solar Energy*, *206*, 35–51. https://doi.org/10.1016/j.solener.2020.05.022
15. Valera, Á., Rodrigo, P. M., Almonacid, F., & Fernández, E. F. (2021). Efficiency Improvement of Passively Cooled Micro-Scale Hybrid CPV-TEG Systems at Ultra-High Concentration Levels. *Energy Conversion and Management*, *244*, 114521. https://doi.org/10.1016/j.enconman.2021.114521
16. Baig, H., Heasman, K. C., Sarmah, N., & Mallick, T. (2012). Solar Cells Design for Low and Medium Concentrating Photovoltaic Systems. *AIP Conference Proceedings, 1477* (1), 98–101. American Institute of Physics. https://doi.org/10.1063/1.4753843
17. Payet, J., & Greffe, T. (2019). Life Cycle Assessment of New High Concentration Photovoltaic (HCPV) Modules and Multi-Junction Cells. *Energies*, *12* (15), 2916. https://doi.org/10.3390/en12152916
18. Grasso, G., Righetti, A., Ubaldi, M. C., Morichetti, F., & Pietralunga, S. M. (2012). Competitiveness of Stationary Planar Low Concentration Photovoltaic Modules Using Silicon Cells: A Focus on Concentrating Optics. *Solar Energy*, *86* (6), 1725–1732. https://doi.org/10.1016/j.solener.2012.03.015
19. Philipps, S. P., Bett, A. W., Horowitz, K., & Kurtz, S. (2015). *Current Status of Concentrator Photovoltaic (CPV) Technology* (No. NREL/TP-5J00-65130). National Renewable Energy Lab. (NREL), Golden, CO (United States).
20. Hamza, M., Kechiche, O. B. H. B., Barkaoui, B., & Sammouda, H. (2017, March). Performance comparison between commercial mono-crystalline and poly-crystalline PV modules under LCPV conditions. In *2017 International Conference on Green Energy Conversion Systems (GECS)* (pp. 1–6). IEEE. https://doi.org/10.1109/GECS.2017.8066261
21. Shanks, K., Senthilarasu, S., & Mallick, T. K. (2016). Optics for Concentrating Photovoltaics: Trends, Limits and Opportunities for Materials and Design. *Renewable and Sustainable Energy Reviews*, *60*, 394–407. https://doi.org/10.1016/j.rser.2016.01.089
22. Amanlou, Y., Hashjin, T. T., Ghobadian, B., Najafi, G., & Mamat, R. (2016). A Comprehensive Review of Uniform Solar Illumination at Low Concentration Photovoltaic (LCPV) Systems. *Renewable and Sustainable Energy Reviews*, *60*,

1430–1441. https://doi.org/10.1016/j.rser.2016.03.032

23. Baig, H., Montecucco, A., Siviter, J., Li, W., Paul, M., Sweet, T., ... & Mallick, T. (2016). Indoor Characterization of a Reflective Type 3D LCPV System. *AIP Conference Proceedings*, *1766* (1). AIP Publishing. https://doi.org/10.1063/1.4962070
24. Schuetz, M. A., Shell, K. A., Brown, S. A., Reinbolt, G. S., French, R. H., & Davis, R. J. (2012). Design and Construction of a~ 7× Low-Concentration Photovoltaic System Based on Compound Parabolic Concentrators. *IEEE Journal of Photovoltaics*, *2* (3), 382–386. https://doi.org/10.1109/JPHOTOV.2012.2186283
25. Mallick, T. K., & Eames, P. C. (2008). Electrical Performance Evaluation of Low-Concentrating Non-imaging Photovoltaic Concentrator. *Progress in Photovoltaics: Research and Applications*, *16* (5), 389–398. https://doi.org/10.1002/pip.819
26. Sonneveld, P. J., Swinkels, G. L. A. M., Van Tuijl, B. A. J., Janssen, H. J. J., Campen, J., & Bot, G. P. A. (2011). Performance of a Concentrated Photovoltaic Energy System with Static Linear Fresnel Lenses. *Solar Energy*, *85* (3), 432–442. https://doi.org/10.1016/j.solener.2010.12.001
27. Cvetkovic, A., Mohedano, R., Gonzalez, O., Zamora, P., Benitez, P., Fernandez, P. M., ... & Miñano, J. C. (2011). Performance Modeling of Fresnel-based CPV Systems: Effects of Deformations under Real Operation Conditions. *AIP Conference Proceedings*, *1407* (1), 74–78. American Institute of Physics. https://doi.org/10.1063/1.3658298
28. Xie, W. T., Dai, Y. J., Wang, R. Z., & Sumathy, K. (2011). Concentrated Solar Energy Applications Using Fresnel Lenses: A Review. *Renewable and Sustainable Energy Reviews*, *15* (6), 2588–2606. https://doi.org/10.1016/j.rser.2011.03.031
29. El Himer, S., Al Ayane, S., & Ahaitouf, A. (2020, September). Optical Modeling and Performance Design of a Fresnel Lens for CPV Units. *IOP Conference Series: Materials Science and Engineering*, *937* (1), 012025. IOP Publishing. https://doi.org/10.1088/1757-899X/937/1/012025
30. Renzi, M., Cioccolanti, L., Barazza, G., Egidi, L., & Comodi, G. (2017). Design and Experimental Test of Refractive Secondary Optics on the Electrical Performance of a 3-Junction Cell Used in CPV Systems. *Applied Energy*, *185*, 233–243. https://doi.org/10.1016/j.apenergy.2016.10.064
31. El Himer, S., El-Yahyaoui, S., Mechaqrane, A., & Ahaitouf, A. (2017). Comparative Study of Two CPV Optical Concentrators, Using a Fresnel Lens as Primary Optical Element. *IOP Conference Series: Materials Science and Engineering*, *186* (1), 012033. IOP Publishing. https://doi.org/10.1088/1757-899X/186/1/012033
32. Ferrer-Rodríguez, J. P., Baig, H., Fernández, E. F., Almonacid, F., Mallick, T., & Pérez-Higueras, P. (2017). Optical Modeling of Four Fresnel-based High-CPV Units. *Solar Energy*, *155*, 805–815. https://doi.org/10.1016/j.solener.2017.07.027
33. Dosymbetova, G., Mekhilef, S., Saymbetov, A., Nurgaliyev, M., Kapparova, A., Manakov, S., ... & Koshkarbay, N. (2022). Modeling and Simulation of Silicon Solar Cells under Low Concentration Conditions. *Energies*, *15* (24), 9404. https://doi.org/10.3390/en15249404
34. Wiesenfarth, M., Steiner, M., Wolf, J., Schmidt, T., & Bett, A. W. (2014). Investigation of Different Fresnel Lens Designs and Methods to Determine the Optical Efficiency. *AIP Conference Proceedings*, *1616* (1), 97–101. American Institute of Physics. https://doi.org/10.1063/1.4897037
35. Jing, L., Liu, H., Wang, Y., Xu, W., Zhang, H., & Lu, Z. (2014). Design and Optimization of Fresnel Lens for High Concentration Photovoltaic System. *International Journal of Photoenergy*. https://doi.org/10.1155/2014/539891
36. Yeh, N. (2010). Analysis of Spectrum Distribution and Optical Losses under Fresnel Lenses. *Renewable and Sustainable Energy Reviews*, *14* (9), 2926–2935. https://doi.org/10.1016/j.rser.2010.07.016

37. Drury, E., Lopez, A., Denholm, P., & Margolis, R. (2014). Relative Performance of Tracking versus Fixed Tilt Photovoltaic Systems in the USA. *Progress in Photovoltaics: Research and Applications*, *22* (12), 1302–1315. https://doi.org/10.1002/pip.2373
38. Kumar, V., Shrivastava, R. L., & Untawale, S. P. (2015). Fresnel lens: A promising Alternative of Reflectors in Concentrated Solar Power. *Renewable and Sustainable Energy Reviews*, *44*, 376–390. https://doi.org/10.1016/j.rser.2014.12.006
39. Gol, A. E., & Ščasný, M. (2023). Techno-Economic Analysis of Fixed versus Sun-Tracking Solar Panels. *International Journal of Renewable Energy Development*, *12* (3), 615. https://doi.org/10.14710/ijred.2023.50165
40. Akisawa, A., Hiramatsu, M., & Ozaki, K. (2012). Design of Dome-Shaped Non-imaging Fresnel Lenses Taking Chromatic Aberration into Account. *Solar Energy*, *86* (3), 877–885. https://doi.org/10.1016/j.solener.2011.12.017
41. Goldstein, A., & Gordon, J. M. (2011). Tailored Solar Optics for Maximal Optical Tolerance and Concentration. *Solar Energy Materials and Solar Cells*, *95* (2), 624–629. https://doi.org/10.1016/j.solmat.2010.09.029
42. El Himer, S., Ahaitouf, A., El-Yahyaoui, S., Mechaqrane, A., & Ouagazzaden, A. (2012). A Comparative of Four Secondary Optical Elements for CPV Systems. *AIP Conference Proceedings*, *30003*. https://doi.org/10.1063/1.5053502
43. Pham, T. T., Vu, N. H., & Shin, S. (2019). Novel Design of Primary Optical Elements Based on a Linear Fresnel Lens for Concentrator Photovoltaic Technology. *Energies*, *12* (7), 1209. https://doi.org/10.3390/en12071209
44. Bione, J., Vilela, O. C., & Fraidenraich, N. (2004). Comparison of the Performance of PV Water Pumping Systems Driven by fixed, Tracking and V-Trough Generators. *Solar Energy*, *76* (6), 703–711. https://doi.org/10.1016/j.solener.2004.01.003
45. Sumathi, V., Jayapragash, R., Bakshi, A., & Akella, P. K. (2017). Solar Tracking Methods to Maximize PV System Output–A Review of the Methods Adopted in Recent Decade. *Renewable and Sustainable Energy Reviews*, *74*, 130–138. https://doi.org/10.1016/j.rser.2017.02.013
46. Larico, E. R. A., & Gutierrez, A. C. (2022). Solar Tracking System with Photovoltaic Cells: Experimental Analysis at High Altitudes. *International Journal of Renewable Energy Development*, *11* (3), 630. https://doi.org/10.14710/ijred.2022.43572
47. Renno, C., & Perone, A. (2021). Experimental Modeling of the Optical and Energy Performances of a Point-Focus CPV System Applied to a Residential User. *Energy, 15*, 119156. https://doi.org/10.1016/j.energy.2020.119156