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Reducing the Solar Tracker Power Consumption of LCPV using Π-Shaped Optics

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Abstract- As low concentrating photovoltaic is one of the efficient ways to improve the performance of current PV systems, improving their design is a significant task. Many Fresnel-lens based CPV systems have the problem related to low acceptance angle and due to this, the system requires high-precision solar tracking systems. In this work, to reduce the complexity of the Fresnel-based CPV systems a polycrystalline solar cells, which reduce the system cost, were used, Π-shaped optical system, which has high acceptance angle, was proposed and a dual-axis solar tracking system, which consume less energy, was obtained and the system was modeled in COMSOL Multiphysics. Optical efficiency of the Π-shaped optical systems by azimuth and altitude changes dramatically if the incidence angle is higher. In terms of the reflective surfaces, the optical efficiency of the optical system gets higher and optical efficiency is more than 80% at the range $-22° < a < 22°$ of the incidence angle. If incidence angle is lower, in our case is 5°, the motor power will be higher as the activation increment is more due to the system moves by 5°, but it takes less time compared to other incidence angles. The optical efficiency is more than 90% if the incidence angle is 20° and the system uses 17% less energy than if the incidence angle is 5°.

Keywords LCPV, solar trackers, energy consumption, optical efficiency, light incidence angle.

1. Introduction

Fossil fuels meet approximately 80% of the worldwide energy demand, but their resources are finite, and they have negative impacts on the environment. [1]. Hence, it is essential for humanity to seek alternative energy sources to ensure a future that is both environmentally clean and sustainable. In this context, solar energy emerges as the optimal solution among various alternative renewable energy sources due to its widespread accessibility, versatility, and environmentally friendly characteristics. [2]. Currently, the efficiency of PV panels is considered as lower as 0.015% of solar energy is used for producing electricity, 0.3% for heating, and 11% of solar energy is utilized in natural photosynthesis of biomass [3]. The challenges in the efficiency of current PV systems are low irradiance of incident sunlight, high cost of efficient solar cells, complexity and non-affordability of high-precision solar tracking systems. Today researchers are working on improving the electrical conversion of PVs [4].

One of the ways to improve the performance of PV systems is to apply a concentrating optical element such as mirrors or lenses to harvest more sunlight on the surface of a solar cell [5]. CPVs are divided into three main groups depending on their concentration ratio: low concentrating photovoltaics, medium concentrating photovoltaics, high concentrating photovoltaics [6]. Concentrating photovoltaic (CPV) systems are becoming more popular and getting improved by various methods. There are many optical designs created for CPVs depending on the price, type of a solar cell used, concentration ratio and optical efficiency.

The most effective type of current CPVs is considered HCPV with its concentration ratio is more than 300, but they are not used in the industry [7]. Most of them are based on the Fresnel lens optics, for example, [8] presented a 31.5% efficient 700X module with triple-junction III–V cells and silicone-on glass (SOG) Fresnel lenses having a±0.6 acceptance angle. Since the altitude of the Sun changes over time, this acceptance angle is small to work the system without syn tracking system. Usually in order to widen the acceptance angle the CPV system, a non-imaging Fresnel lens as the primary optics and an inverted pyramid kaleidoscope as the secondary optics are used in [9] and the module was a 35% efficient with the acceptance angle of ±1.1 at 1000x. They are usually constructed with expensive, small multi-junction solar cells [10], therefore, they have small acceptance angles and usually need a high-accuracy dual-axis solar tracking system. Taking into account these facts, HCPV is considered as a high-cost system in terms of the high price of a solar cell and solar tracker [11].

The work [12] investigates the dependence of concentration ratio and acceptance angle of CPCC LCPVs and concentration ratio depends on the size of the optical elements. The more concentration ratio the smaller acceptance angle. The article [13] investigated a V-trough concentrator's optimal geometrical parameters to get wider acceptance angle and higher optical efficiency and reported that while the light incidence angle is smaller than the concentrator's acceptance angle, then the reflected light will be uniformly distributed on the surface of the solar cells.

Compared to HCPV and MCPV, LCPV (2-10 suns) is simpler and more affordable due to its lower installation cost, higher tracker tolerances, lower cost optics [14]. Moreover, LCPV systems can be installed with crystalline silicon solar cells which are the cheapest cells. The work [15, 16] showed that when using Fresnel lens as a concentrator for polycrystalline solar cells, it is possible to get LCPV systems which can generate 27% more energy than a non-concentrated silicon solar cell. LCPV systems due to their concentrating optics, do not require accurate solar tracking systems [17].

Another way is to move the system directed to the Sun [18]. There are two main types of solar trackers: single-axis [19], dual-axis solar trackers [20, 21]. Single-axis sun trackers have only one degree of freedom of motion and they can track the diurnal trajectory of the sun's motion in only one direction [22] and can convert 20% more energy compared to stationary photovoltaic systems. Dual-axis solar trackers can be able to track the Sun following two axes simultaneously, Left-Right (azimuth angle) and Up-Down (altitude angle) direction [23]. Without considering the extra manufacturing cost of dual-axis trackers, they improve the system performance by 82% compared to fixed panels which are 15-20% more than a single-axis solar tracking system. The work [24] reviewed all recent solar tracking systems for PV and CPV systems and concluded that double axis solar trackers always achieved good performances with greater efficiencies between 20% and 50% energy gains compared to fixed flat PV panels and/or CPV systems. Some papers [25] prove that double axis solar trackers are not only more efficient and can also be cost-effective in some cases. The article [26] states that when using point focus concentrators single-axis solar trackers are not efficient as double axis trackers have maximum solar radiation absorption capabilities and the subsequent production of maximum energy output. Although they have higher efficiency than single-axis solar trackers, their energy consumption is much more. Vast majority of existing solar trackers use sun sensors which generate a composite signal that triggers the motors or actuators to move their fixtures following the solar radiation beam and separate power supply (24, 27, 28). It means, they consume external power to work and they need 3.5-5 years of payback cost on tracker investment [29]. There are some methods and algorithms to optimize the work of solar tracking systems [30, 31, 32], but they are more complicated. It means, reducing the cost of the system by reducing the amount of energy consumed by solar trackers using cheaper and easier methods is important. To tackle this issue, one solution might be designing CPV optics, which shows high optical efficiency at some deviation of incident sunlight. To do that, we have to design an optical system which can work at higher incidence angles without tracking.

We proposed Π-shaped LCPV system with dual-axis solar tracking system which use less energy due to the optical design of the concentrator. The Π-shaped LCPV system contains nine polycrystalline silicon solar cells, which one central cell is considered as main one, others work as additional cells which helps not to lose the rays which is not perpendicular to the surface of Fresnel lens. Π-shaped optics consists of a Fresnel lens. A solar tracker is an essential component in such types of concentrators. Substantial amount of energy is consumed in tracking. Worldwide researchers endeavor to mitigate the tracker power consumption. It is very difficult to reduce the power consumption due to the bulky, heavy and odd shape of reflectors, on the other hand Fresnel lens supports substantial reduction in power consumption due to its favorable aerodynamic streamlined shape [33]. In this work, not heavy four reflective surfaces are also placed which help to redirect the sunlight to the cell and it also helps to reduce the work of solar tracking. Modeling is carried out in COMSOL Multiphysics. The proposed LCPV system with Π-shaped optics can overcome problems of current PV modules in terms of that the proposed system increase the incident solar irradiance, use affordable solar cell and the simple optics can reduce the solar consumption of the solar tracking system.

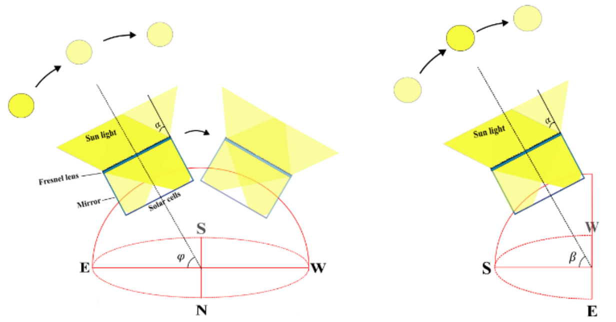
2. The Π-Shaped Optical System with A Dual-Axis Solar Tracking System

The proposed Π-shaped optical design for LCPV consists of a Fresnel lens with the size of 150x150 mm and four reflective surfaces with the size of 150x150 mm which help to redirect the incident rays to the solar cells when light incidence angle is not zero. Moreover, the system has nine polycrystalline solar cells which help not to lose the light rays which are not directed to the central solar cell. The geometrical concentration ratio is an important parameter of concentrating photovoltaic systems and it can be defined as:

$$C_{geo} = \frac{A_L}{A_C} \tag{1}$$

where, $A_L$is the area of lens, A_C is the lighted area. The geometrical concentration ratio of the Π-shaped LCPV at zero incidence angle is calculated and equals 4.

Even though concentrating optics can help to get more sunlight on the surface of a solar cell, when using Fresnel lens, the optic might concentrate the sunlight out of the solar cell at wider incidence angles. Under perpendicular incident sunlight the system works as a system only with Fresnel lens, but as shown in Figure 1, when the Sun moves during the day the main solar cell will not be properly lighted, as a result the overall performance of the system reduces, it affects the output characteristics of the LCPV and might occur the degradation of a solar cell. In terms of the reasons, the system requires a solar tracking system which tracks the Sun movement during the day. The dual-axis solar trackers ensure that the solar panel absorbs maximum sunlight to generate maximum electricity.



a) b)

Fig. 1. The movement of LCPV system based on Fresnel lens with reflective surfaces a) azimuth, b) altitude.

In order to create the system with a solar tracker we need to know how the Sun moves during the day. As dual-axis angle moves the LCPV system by φ azimuth and β altitude angles, we have to find the angles:

for local Total time > 12.00 hr

$$\varphi = 180° + arcco\,s\left(\frac{sin\beta \cdot sinL - sin\delta}{cos\beta \cdot cosL}\right) \tag{2}$$

for local Total time < 12.00 hr

$$\varphi = 180° - arcco\,s\left(\frac{sin\beta \cdot sinL - sin\delta}{cos\beta \cdot cosL}\right) \tag{3}$$

$$\beta = arcsin\,(sinL \cdot sin\delta + cos\omega \cdot cosL \cdot cos\delta) \tag{4}$$

where L- latitude of the location, β is the altitude angle and δ is the declination angle, ω is the hour angle [34].

The Sun's trajectory relative to the Earth in the horizontal coordinate system on June 22, 2023 in Almaty, Kazakhstan is calculated using the Equations (2) - (4). As a result, it was presented that the Sun moves 240° in azimuth, and rises in altitude to a maximum of 70° during the day relative to the Earth. The calculated altitude and azimuth Sun's trajectory were used in modeling the optical characteristics of the system on the COMSOL Multiphysics software with the Ray Tracing method. Azimuthal and altitudinal optical efficiency and solar tracking consumption of the LCPV system at a certain range of the light incidence angle and time to move the system to a certain incidence angle were found and the power consumed by solar tracker motors to move azimuthal and altitudinal over time were modeled.

The power consumption over time of the motor actuators of the solar tracking system with the load was determined and is shown in Figure 2.

From the power consumption nature of the solar tracking system actuators, we can see that it requires high power consumption at the initial time values, and the power consumption decreases and stabilizes over time. The nature of this power consumption provides some opportunities. It is known that most of the traditional solar tracking systems work in the solar tracking mode, that is, the more frequently the actuator is activated, the higher values of power are used, and it can be seen that the energy consumption is relatively higher when integrated over the total time. If we reduce the number of activations of the actuator per day then you can save energy.

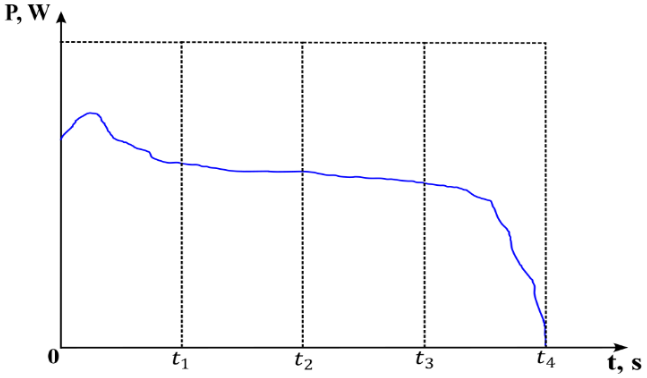


Fig. 2. The power consumption over time of the motor actuators of the solar tracking system with the load.

The time required to move the tracker in the desired position (or angle) is determined. The energy consumption E of electric motors is determined as the integral of P power over time t multiplied by the number of activations N as shown in Equation (5):

$$E = N\int_{t_1}^{t_2} Pdt \tag{5}$$

Depending on the calculated trajectory of the Sun, the number of activations and energy consumption of the dual-axis solar tracker during the day were calculated, and dependencies were established for different angles of rotation.

3. Optical Characteristics of the Π-Shaped Optical Systems

The optical efficiency of the Π-shaped LCPV was obtained using Ray Tracing simulation in the COMSOL Multiphysics software, and its dependence on the light incidence angle was established as shown in Figure 3.

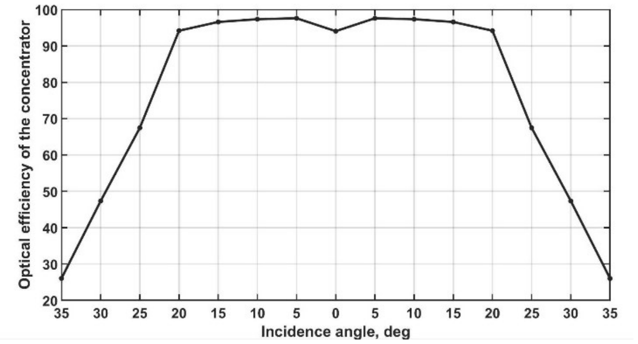


Fig. 3. Dependence of optical efficiency of concentrating elements on light incidence angle.

From the Figure 3, it can be seen that when the light incidence angle is zero, the optical efficiency of the concentrator is slightly lower than the optical efficiencies at the range $0° < a < 20°$ of the incidence angle. In terms of the reflective surfaces, the optical efficiency of the optical system gets higher and optical efficiency is more than 80% at the range $-22° < a < 22°$ of the incidence angle. The wider range of incidence angle at high optical efficiencies (more than 90%), the lower accuracy of a solar tracking system is required.

Due to the fact that the proposed Π-shaped optical system is used in a dual-axis solar tracking system, the change of the optical efficiency in terms of azimuth and altitude was considered. High optical efficiency has to be remained by azimuth and altitude as this keeps the balance between optical part and solar tracking part of the LCPV. If optical efficiency is higher when moving the LCPV system, the overall performance of the LCPV will be higher.

When moving the system by azimuth or altitude, it is important to evaluate the optical efficiency of the system, because optical efficiency affects concentration ratio of the concentrator and it has to be high, usually 90-100%. Figure 4 shows the change of optical efficiency by changing the azimuth angle by incidence angles 5°, 20°, 25°. As it can be seen, the lower the light incidence angle, the higher optical efficiency of the system. When the incidence angle is 5°, optical efficiency is maximum.

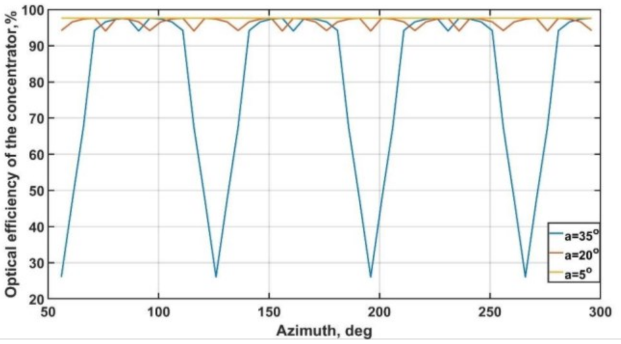


Fig. 4. Optical efficiency of the optical system by azimuth at different incidence angles.

Figure 5 presents the optical efficiency analysis when the system moves during the day. During noon, optical efficiency changes more quickly than in the morning and afternoon in terms of the velocity of the Sun's movement relative to the Earth.

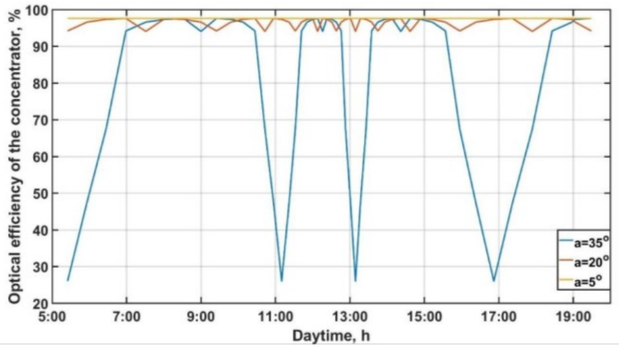


Fig. 5. Optical efficiency of the optical system by azimuth during the day at different incidence angles.

As Figure 6 shows, the Sun doesn't move much relative to the Earth by altitude, therefore the optical efficiency doesn't change frequently. At 5°, 20° the optical efficiency is more than 90% and that's good performance but if the altitude angle is 35° the optical efficiency of the optical system reduces to 30%, therefore, the dual-axis solar rechecking system has to rotate the system by 5° or 20°.

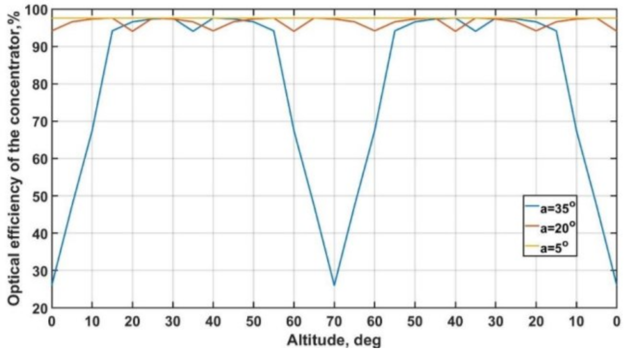


Fig. 6. Optical efficiency of the optical system by altitude at different incidence angles.

Moreover, in Figure 7 we can see the drop in optical efficiency at around 11 am if the incidence angle is 35°. It shows that in order to keep optical efficiency of the concentrator at high value, the light incidence angle must be lower and the solar tracking system has to move the system by smaller angles than 35°. When the optical efficiency changes more frequently and sharply, non-uniformity of solar radiation on the surface of the solar cells may occur and the nonuniform sunlight leads to a decrease in the generated electricity by the solar cells and they may lose their properties.

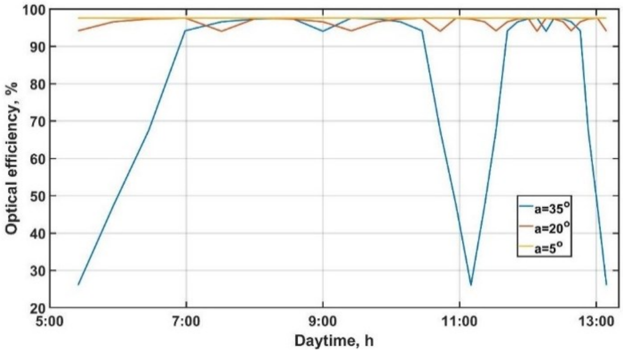


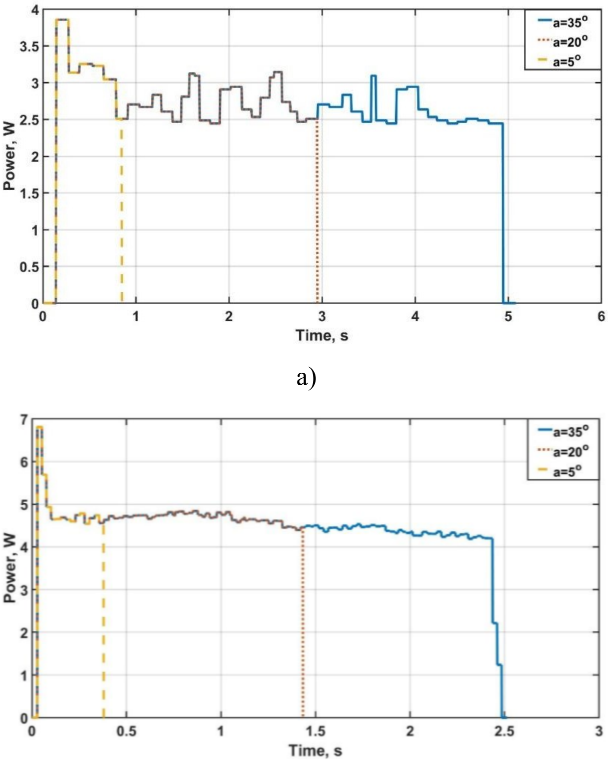
Fig. 7. Optical efficiency of the optical system by altitude during the day at different incidence angles.

4. Power Consumption of a Solar Tracker for the Π-Shaped LCPV Systems

Apart from optical efficiency of the concentrator, it is necessary to assess the motor power consumed to move the system for a certain angle. Figure 8 shows the amount of power consumed by the motor of the solar tracker with real load which was investigated by us [35] and time spent to move the certain angle by azimuth and altitude. The dual-axis solar tracker needs more time if the incidence angle is higher 35° since moving the whole LCPV system by 35° is more difficult, but consumes less power since it will be activated less frequently. If incidence angle is lower, in our case is 5°, the motor power will be higher as the activation increment is more due to the system moves by 5°, but it takes less time compared to other incidence angles.

The solar tracker gets little time to move the whole system by 5°, therefore, the motor needs more energy as the motor uses more energy at the beginning of activation and the sum of the power of every activation will be higher than the power consumption of changing by 20° or 35°. The next task is to investigate the number of activations at different incidence angles and sum the power consumed by the motor of the solar tracker.

Figure 9 shows the number of activations depending on different incidence angles, the narrower the incidence angles, the greater number of activations is needed to operate the solar tracker. If the incidence angle is 5°, the solar tracker activates 21 times by azimuth, 13 times by altitude a day. If the incidence angle is 35°, the solar tracker switches 3 times a day by azimuth, once a day by altitude.

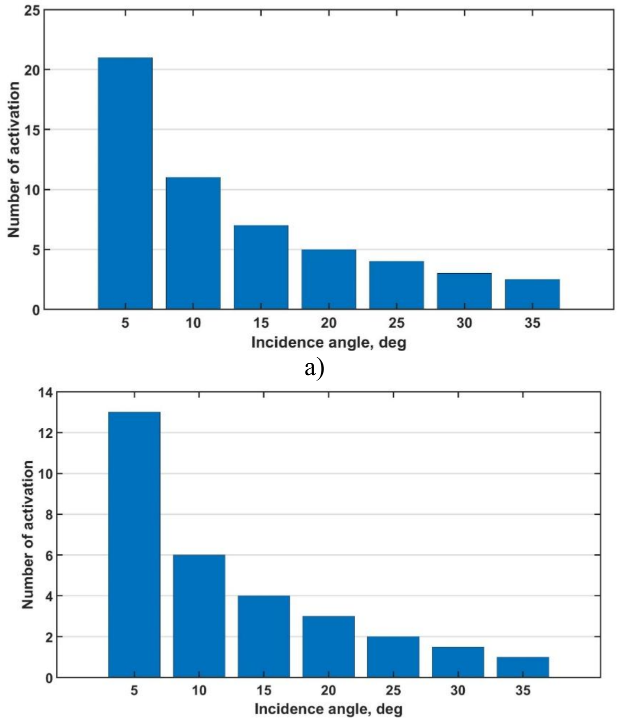


b)

Fig. 8. Tracker motor power over time: a) azimuth, b) altitude

The energy consumption of electric motors has to be calculated during the day and we have to find optimal incidence angle for our proposed Π-shaped LCPV system. From the Equation (4), we can see energy consumption of the dual-axis solar tracker that besides power, the number of activation and time spent to move the system are important factors.

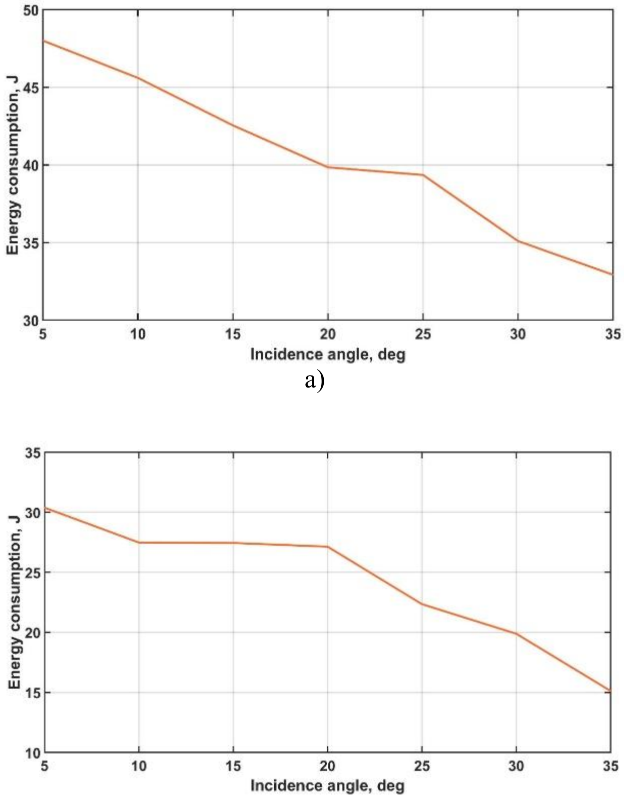
As we concluded earlier, when the motor of the solar tracking system activates frequently, the overall energy consumption of the dual-axis solar tracking system increases. If the angle which the solar tracker rotates is wider, the motor needs more power and activation increments will be less and consumes less energy, but the optical efficiency of the system reduces (Figure 4-7). Therefore, it is very important to keep the balance between motor power and activation increment of the dual-axis solar tracking system.



b)

Fig. 9. Dependence of the number of solar tracker activation on incidence angle a) azimuth, b) altitude.

As a result of calculations using Equation (4), Figure 10 shows the energy consumption of the solar tracking system by azimuth (Figure 10a) and altitude (Figure 10b) at different incidence angles.



b)

Fig. 10. Energy consumption of the dual-axis tracking system at different incidence angles a) azimuth, b) altitude.

Figure 11 shows the total energy consumption of both tracking systems. If the incidence angle is 5° degree, the solar tracking system uses more energy because the number of activations is greater. If the incidence angle increases, the energy consumption of the dual-axis tracker reduces. However, optical efficiency of the system decreases. It means, there must be an incidence angle which we can get higher optical efficiency using less energy.

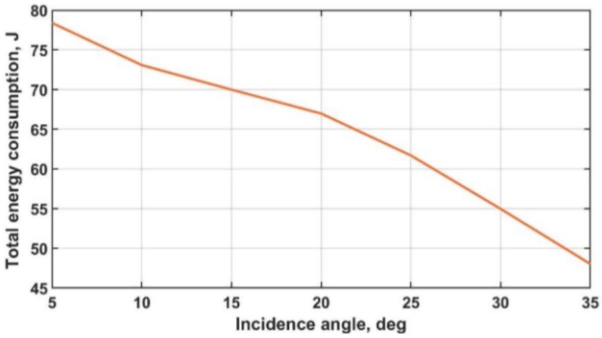


Fig. 11. Total energy consumption of the both tracking system.

Figure 12 shows the total energy consumption of the dual-axis solar tracking system at different incidence angles. The energy is consumed at 5° incidence angle is considered as 100% and is compared with other incidence angles. Accordingly, we can reduce the energy consumption by increasing the incidence angles in terms of the Π-shaped optical system. As Figure 2-5 show, the optical efficiency is more than 90% if the incidence angle is 20° and the system uses 17% less energy. When using Π-shaped optical system for LCPV, constantly moving the tracker for small degrees is not optimal, moving bigger degrees not losing optical efficiency of the system reduces power consumption of the solar tracker. It means that we could reduce the work of the solar tracker in terms of optical design.

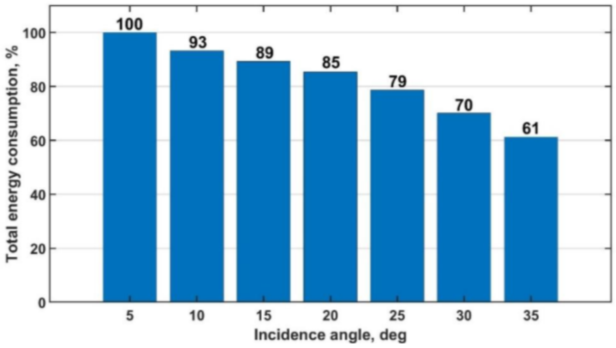


Fig. 12. Total energy consumption comparison of the dual-axis tracking system at different incidence angles.

5. Discussion of Findings

In this work, the optical efficiency of the Π-shaped optical system based on the Fresnel lens proposed for the LCPV was determined using the COMSOL Multiphysics program at different incidence angles. The trajectory of the Sun during the day was calculated, and according to the obtained results, the electricity consumption in the case of using tracker actuators at different incidence angles was calculated, during the study, the following results were achieved:

- The optical efficiency of the proposed Π-shaped optical system is not less than 90% at the range 0-20 degrees of the light incidence angles;
- In terms of the reflective surfaces, the optical efficiency of the optical system gets higher and optical efficiency is more than 80% at the range -22°<a<22° of the incidence angle;
- The optical efficiency is maximum if the light incidence angle is 5°;
- If incidence angle is lower, in our case is 5°, the motor power will be higher as the activation increment is more due to the system moves by 5°, but it takes less time compared to other incidence angles;
- The optical efficiency is more than 90% if the incidence angle is 20° and the system uses 17% less energy than if the incidence angle is 5°.

It has been proved that in case of using the proposed optical system, it is possible to reduce the cost of the system due to reducing the power consumption of the solar tracking system while keeping the optical efficiency of the optical system at a high level.

Most of the Fresnel lens-based concentrating optics face the problem related to low or narrow acceptance angle (limit of the incidence angle), which doesn't exit ±1°, of the concentrating optical system and because of that the systems have to use high-accuracy solar tracking systems and usually the solar tracking systems use some optimization techniques to reduce its energy consumption [8-11]. In this work, proved that using just reflective mirrors with Fresnel lens, a low concentrating photovoltaic system can be constructed and the system can work at wider incidence angles keeping the high optical efficiency and in terms of the benefits, the dual-axis tracking system of the LCPV consumes less energy. Another advantage of the work compared to others, which use costly multi-junction solar cells, is that the Fresnel lens-based CPV system uses cheap polycrystalline silicon solar cells which also reduces the system cost. Due to the above-mentioned benefits of the work, the Fresnel-based CPV is not expensive, not complex and not difficult to construct and develop.

6. Conclusion

A polycrystalline Π-shaped LCPV with a dual-axis solar tracking system was modeled in COMSOL Multiphysics. Optical efficiency of the Π-shaped optical systems by azimuth and altitude changes dramatically if the incidence angle is higher. In terms of the reflective surfaces, the optical efficiency of the optical system gets higher and optical efficiency is more than 80% at the range -22°<a<22° of the incidence angle. The power of the solar tracking motor is higher and it takes less time for moving the LCPV system at low incidence angles. The number of solar tracker activation was greater when incidence angle is lower. If incidence angle is lower, in our case is 5°, the motor power will be higher as the activation increment is more due to the system moves by 5°, but it takes less time compared to other incidence angles. The optical efficiency is more than 90% if the incidence angle is 20° and the system uses 17% less energy than if the incidence angle is 5°.

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