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The Use of Fresnel Lenses to Improve the Efficiency of Photovoltaic Modules for Building-integrated Concentrating Photovoltaic Systems

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ABSTRACT

Nowadays, building-integrated solar systems (i.e. photovoltaic modules installed directly in the façades) and concentrating solar systems are more popular. This paper defines the possibility of using Fresnel lens to improve the efficiency of building integrated photovoltaic modules. Both dynamic simulations (done using TRNSYS software) and experimental results (conducted on dedicated set-up with linear Fresnel lens) were described. It can be concluded, that Fresnel lenses allow improving the overall efficiency of the building integrated photovoltaic systems – during conducted tests, the performance of the tested photovoltaic module increased by about 7%.

KEYWORDS

Renewable energy sources, Solar energy, Photovoltaic, Concentrating solar systems, Fresnel lenses, Building-integrated concentrating photovoltaic systems.

INTRODUCTION

The number of solar energy systems applied in buildings has increased over the last two decades. Such systems are mainly placed on roofs and used to produce heat or electricity. Actually, more popular are building-integrated solar systems [i.e. Photovoltaic (PV) modules installed directly in the façades] and concentrating solar systems [thermal, PV and Photovoltaic thermal (PV/T)] [1]. Parabolic-trough concentrators, parabolic-dish concentrators, Fresnel lenses and other concentrating devices, can be applied both to electricity and heat generation, as well as to control the light and the temperature of internal building spaces covered with transparent materials [2]. From available solutions, Fresnel lenses seem to be one of the best because of such advantages as small volume, light-weight, mass production with low cost and effectively

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increase the energy density [3]. For these reasons, the possibility of the use of Fresnel lenses in Building-integrated Concentrating Photovoltaic (BICPV) systems is discussed in this paper.

Fresnel lenses consist of discrete concentric prism elements patterned on a superstrate. Figure 1 presents a cross section of a spherical Fresnel lens in comparison to cross section of a conventional spherical plano-convex lens of equivalent power [4].

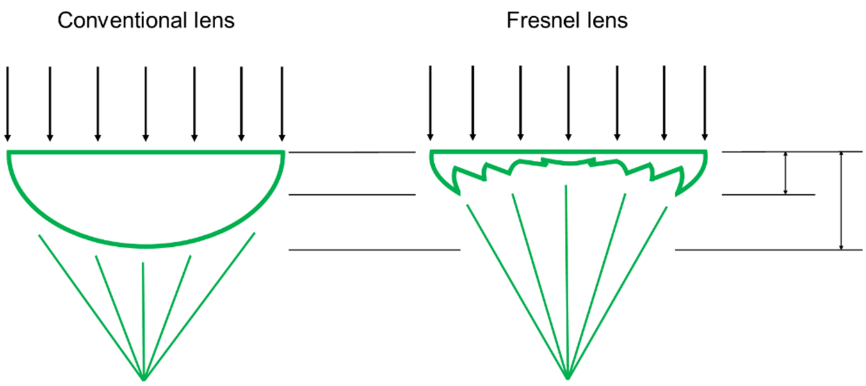

Figure 1. The comparison of conventional and Fresnel lens

The first applications using Fresnel lenses for Concentrated Photovoltaic (CPV) power generation have been constructed and tested in 1960 [5]. The efficiency and intensity variations of a circular Fresnel lens as a solar concentrator have been experimentally and analytically determined by Harmon [6]. A PV concentrator array, based on the use of an acrylic Fresnel lens to concentrate sunlight on high intensity solar cells and optimized to obtain economical PV power generation, was designed in 1978 [7]. Well known, commercially introduced concentrator technology for PVs, was proposed by O'Neil [8]. The curved prismatic Fresnel lens comprised a substantially smooth, convex outer surface and a plurality of prisms arranged side-by-side along a curve on the inner surface to direct incoming light to a common area. A few years later, a refractive optical concentrator for focusing solar energy on small focal spots, which was a linear Fresnel lens optically cross-coupled with simple cylindrical lenses, was developed [9]. The cylindrical system of Fresnel lens-absorber with uniform concentration was considered by Mijatovic *et al.* [10]. In 1980, polar axis tracking concentrator equipped with 36 Fresnel lenses (with dimension of 0.4 × 0.4 m) and cells was designed to obtain the uniform light distribution. The power of this concentrator was 300 W and it was about 50% higher than that of the commercial lenses [11]. A 1 kW_p concentrating PV array with 180 square Fresnel lenses and AlGaAs/GaAs concentrator solar cells has been constructed and presented in [12]. The maximum output power from the best concentrator cell was 9.1 W with the efficiency of 22.6%. An array output power of 977 W had been obtained.

Further research and development work was directed to many fields such as bifocal Fresnel lenses, space concentrator PV modules, field test of concentrator PV system [13, 14], etc. Ninety small PV concentrator designs [including point-focus Fresnel lenses with two-axis tracking and linear Fresnel lens with solid Compound Parabolic Concentrator (CPC) secondaries and two-axis tracking] were compared by Whitfield *et al.* [15]. The first proposition of a novel, high-efficiency, extremely light-weight, robust stretched Fresnel lens solar concentrator for space power applications was presented by Whitfield *et al.* [15, 16]. Tests of the stretched lens array allowed to obtain over 27% net solar-to-electric conversion efficiency for space sunlight, and over 30% net solar-to-electric orbit [17]. New kind of band-focus Fresnel lens solar concentrator was proposed by Wang *et al.* [18]. Simulation conducted using Monte Carlo Ray Tracing

Method (MCRT) was compared with the linear Fresnel lens. The results showed that spectral concentrating uniformity and optical efficiency of the band-focus Fresnel lens were better than those of the linear one [18]. It was connected with the fact, that traditional Fresnel lenses make lights focus to a point or a line with wedges which are distributed on a plane or a curved surface [19, 20]. As a result, the energy flux densities on solar cells may be non-uniform reducing the efficiency of PV modules [21, 22]. For this problem, the point-focus Fresnel lens was improved – rays were focused through the new lens to a square which had the same size as a solar cell [23]. In El Himer *et al.* [24], the performances of two optimized reflective secondary optics elements a CPC and a Cone for use in a concentrator PV system were studied using ray-tracing simulation for the same primary optical element: a Fresnel lens. The power distribution at the end of the concentrator was more uniform in the case of the cone. It was also found that the length and the input radius of each optical element decrease when the Fresnel lens diameter increases.

The analysis of a one-year set of environmental condition data of the University of Miyazaki, Japan, where the CPV system was installed, was shown in Al Husna *et al.* [25]. The average photon energy was used to describe the spectrum distribution at the site where the CPV system was installed. A circuit simulator network was used to simulate the CPV system electrical characteristics under various environmental conditions. It was found that the performance ratio of the CPV systems depends on the average photon energy level rather than the cell temperature. Another practical study, aimed to design and construct a solar powered desalination system using Fresnel lens, was shown by Han *et al*. [26]. The desalination system was composed of the solar concentrator, solar still and the condenser system. The Fresnel lens was made of acrylic plastic and was an effective solar concentrator. The highest mean efficiency of the designed set-up was 34.82%. The water produced by the solar powered desalination system using Fresnel lens passed the standards set by World Health Organization for drinking water. In Al-Dohani *et al.* [27], a proto-Fresnel lens power house was developed to generate electricity. The focused heat from the Fresnel lens was used to heat the molten salt in a heat exchanger to produce steam. The generated steam was used to run the steam engine coupled to a generator. In the current work, a maximum power of 30 W was produced.

Besides the number of experimental investigations, there are also many studies conducted using simulation software. One of the simulation software dedicated to solar systems is TRNSYS [28]. Using TRNSYS, the behaviour of PV modules can be predicted under real, dynamic conditions. Among published work on models of PV cells, a five-parameter model is mostly used [29]. This model is based on an equivalent circuit of a one diode-model. Such an approach requires a few parameters for predicting the energy production of PV power plants [30, 31]. The previous study was directed to many fields, such as bifocal Fresnel lens test for multijunction solar cells [32] and space concentrator PV modules [33]. Predicted performance of a grid connected PV system using TRNSYS was compared with measured data. The difference between predicted performances was between 1% and 2% [34]. Such a high accuracy of TRNSYS simulations makes TRNSYS software suitable for analysing different aspects of the PV systems operation. In this paper, the operation parameters of PV module in different conditions (including various slopes and azimuths of PV module) were compared. Obtained in this way, the results were a basis for further experiments conducted on the dedicated set-up.

METHODS

The study was divided into two parts: dynamic simulations of PV module operation in various conditions (conducted using TRNSYS software) and experiments (carried out using dedicated set-up).

Dynamic simulation software

Transient System Simulation Tool (TRNSYS) is a transient systems simulation program suited to detailed analyses of any system whose behaviour is dependent on the passage of time, e.g. all thermal and renewable generation systems, except nuclear, wave, tidal and hydro power installations. TRNSYS model simulates the performance of the entire energy-system by breaking it down into individual components. It may be used for analysing single-project, local, community, or island energy-systems.

The modelling and the simulation of the PV cell operation were conducted using built-in library components with parameters corresponding with the used device. The weather data, containing information for Krakow-Balice, was imported from Meteonorm database.

The operation of the PV cell is represented in TRSYS by the Type 194. This component uses a five-parameter equivalent circuit model to determine the current and power of the PV array at a specified voltage as well as current and voltage at the maximum power point [35]. The equivalent circuit diagram, which is the basis for the considering model, is shown in Figure 2.

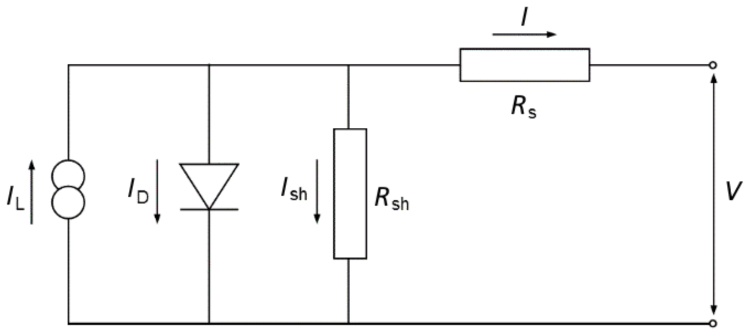

Figure 2. Equivalent electrical circuit of PV module

The current-voltage (I-V) characteristics of a PV array vary with environmental conditions (mostly depending on the insolation and temperature). The model determines the I-V curve and thus the power delivered to the load using five parameters: the light current (I_L), the diode reverse saturation current (I_0), the series resistance (R_s), the shunt resistance (R_{sh}) and the modified ideality factor (a) (which is linear function of cell temperature). Reference values of these parameters are determined for a Standard Rating Condition (SRC). Three current-voltage pairs are available from the manufacturer at SRC: the short circuit current, the open circuit voltage and the current and voltage at the maximum power point. A fourth piece of information results from recognizing that the derivative of the power at the maximum power point is zero. Simultaneously simulation of both the inverter and PV array allows including the limitations of the inverter: minimum and maximum allowable input voltage and maximum allowable input power.

The current-voltage equation for the circuit shown in Figure 3 is as follows:

$$I = I_{\mathrm{L}} - I_0\left(e^{\frac{V+IR_{\mathrm{s}}}{a}} - 1\right) - \frac{V + IR_{\mathrm{s}}}{R_{\mathrm{sh}}} \tag{1}$$

where I_L [A] is the module photocurrent, I_0 [A] is the diode reverse saturation current, V [V] is the voltage, I [A] is the current, R_s [Ω] is the module series resistance, R_{sh} [Ω] is the module shunt resistance and a is the modified ideality factor defined in eq. (2):

$$a = \frac{N_{\mathrm{s}} n_{\mathrm{I}} k T_{\mathrm{c}}}{q} \tag{2}$$

where N_s is the number of modules in series in array, n_I is the diode ideality factor, k [J/K] is the Boltzmann constant, T_c [K] is the module temperature and q [C] is the electron charge constant.

The experimental set-up

The experimental part of this study was conducted using a dedicated set-up equipped with:

- Linear Fresnel lens (with dimensions of 75 × 50 cm);
- 20 W PV cell characterized by an open circuit voltage 12 V and a short circuit current 1.27 A (with dimensions of 45 × 34 cm);
- Pyranometer with measuring range from 0 to 1,999 W/m^2 and resolution 1 W/m^2 (located close to the tested PV cell);
- Pt100 sensor measuring PV cell's surface temperature (placed in the central part of the rear wall of the tested PV cell);
- Pt100 sensor measuring ambient temperature (located close to the tested PV cell);
- Electrical load connected directly with PV cell to perform current-voltage and power-voltage characteristics;
- WAGO PFC200 PLC controller collecting data from pyranometer, temperature sensors, and electrical load;
- PC computer.

The measurements were recorded by means of a modular control and measurement system with a PLC controller. Dedicated algorithm was developed in the CoDeSys software.

The idea of the control and measurement system has been presented in Figure 3.

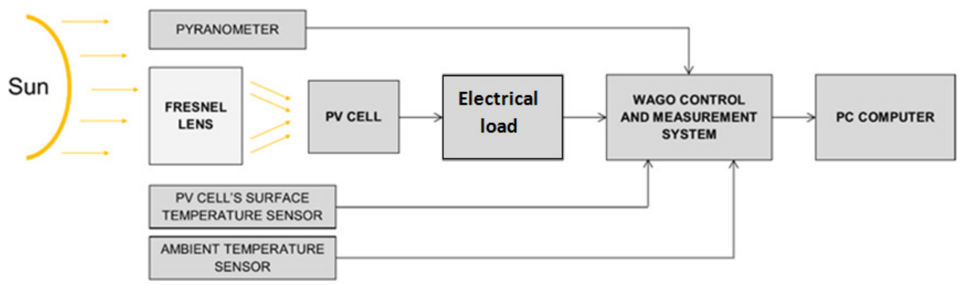

Figure 3. The idea of the system in concern

The set-up was placed at the roof of the building of Faculty of Energy and Fuels, AGH UST in Krakow. The PV modules and Fresnel lens were facing south (tilt angle for a PV module was 90° and its azimuth was 0°). The configuration of the rig is presented in Figure 4.

Figure 4. The configuration of the rig

Such configuration allowed testing the impact of using Fresnel lens on two rows of PV modules. In the first case, Fresnel lens was located coaxially with the PV module, while in the second case – it was placed above the PV module (75 cm higher). In both cases, between Fresnel lens and PV module there was open space, so the share of direct sun radiation reaching to the panel's surface should be included in the considerations.

DISCUSSION OF THE RESULTS

The first part of study was devoted to estimate the performance of tested PV module in different conditions. For this purpose, the TRNSYS software was used. In the next step the possibility of increase in PV module performance using Fresnel lens was tested. Finally, the obtained results were implemented to the model, and additional analysis was carried out.

The results of dynamic simulations

Dynamic simulations allowed comparing the operation parameters of PV module in different conditions.

In such defined PV system, the hourly electricity generation for various slopes and azimuths was modelled. Four slopes were considered: 30°, 45°, 60° and 90° (vertical). From listed angles, the most popular are values in the range of 30-60°. On the other hand, the vertical orientation is true for building-integrated PV systems. The variations in energy generation (dependent on the slope of the considered PV module) is shown in Figure 5 (presented results were obtained for south-oriented PV module).

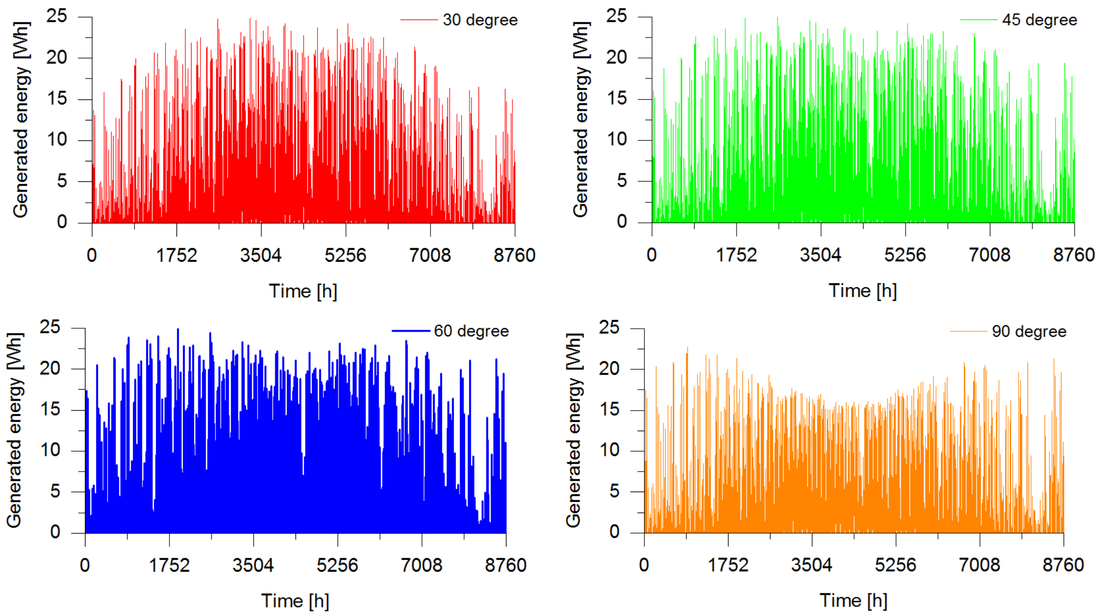

Figure 5. The estimated variations in electricity generation depending on the slope of considered PV module

As we can see in Figure 6, the amount of electricity generated in PV module is not constant during whole year. In the summer, the most effective tilt angle for a PV module is close to 30°, while in the winter it is about 60° (in Polish conditions). If we compare the amount of electricity generated during whole year, we can observe not so significant differences. The amount of electricity generation in the vertically oriented PV module is only about 10% lower than in PV module with tilt angle 45° (28.3 kWh/year in comparison to 31.3 kWh/year). The total yearly electricity generation in the considered PV module, depending on the slope of PV surface, is shown in Table 1.

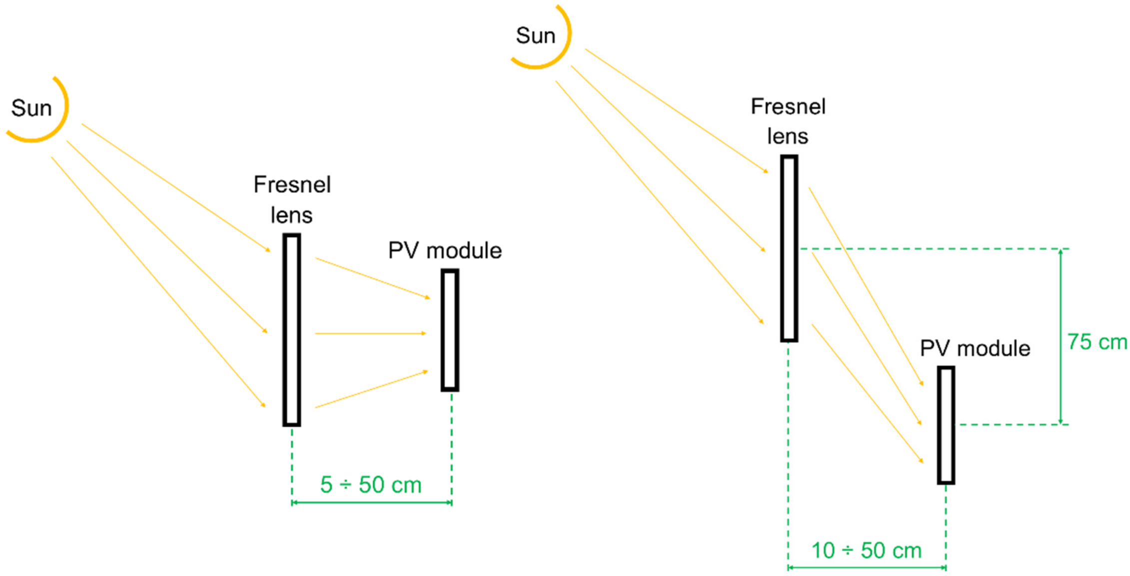

Figure 6. The tested configurations of Fresnel lens and PV module system

Table 1. The yearly electricity generation in the considered photovoltaic module, depending on the slope of PV surface

Slope of the PV surface [degree]	30	45	60	90
Energy generated in tested PV module [kWh/year]	30.6	31.3	31.1	28.3

Not significant reduction in the vertically oriented PV module energy performance confirms that building-integrated PV systems have a sense. On the other hand, it is important to define the performance of tested PV module depending on its azimuth. Four basic orientations (south, east, north and west) were compared. The variations of electricity generation in each case are shown in Figure 7 (presented results were obtained for the situation, when slope of the PV surface is 90°).

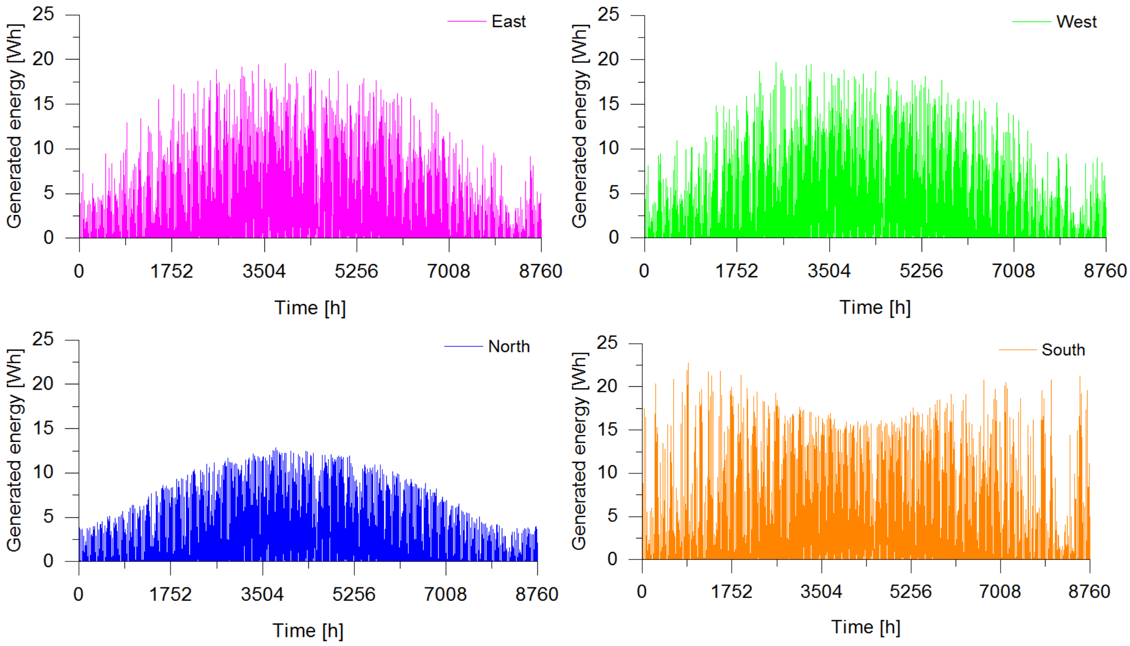

Figure 7. The estimated variations in electricity generation depending on the azimuth of considered PV module

The highest level of electricity generation is observed in the case of south oriented PV module. Moreover, the variations in daily electricity generation are lower in comparison to other considered azimuths. The total yearly electricity generation in the considered PV module, depending on the azimuth of PV surface, is shown in Table 2.

Table 2. The yearly electricity generation in the considered PV module, depending on the azimuth of PV surface

Azimuth of the PV surface [degree]	0 (South)	–90 (East)	180 (North)	90 (West)
Energy generated in tested PV module [kWh/year]	28.3	24.3	19.8	25.0

On the other hand, the south buildings' facades are commonly occupied by number of windows. From this standpoint, it is not possible to use whole area of the wall for PV modules installation. Therefore, the use of east- or west-oriented facades is also popular in the case of Building-integrated Photovoltaics (BIPV) systems.

The experimental results

The possibility of increase in the energy performance of the considered PV module was tested in the second part of the investigation. Figure 8 presents results of measurements made using Fresnel lens placed parallel to the PV module. The direct sun radiation during measurements was in the range 590-610 W/m^2. The distance between Fresnel lens and PV module was varied in the range from 5 to 50 cm. The I-V and P-V characteristics show that too close location of the Fresnel lens was limiting the sun radiation reaching to the PV surface (without concentrating effect) and consequently the generated power. On the other hand, the location of the Fresnel lens in distance more than 40 cm improved the PV module efficiency. The power in Maximum Power Points (MPP) rises from 10.0 W (reaches without Fresnel lens) to 10.4 W (when distance between Fresnel lens and PV module is 40 cm) and 10.7 W (when distance is 50 cm). It is respectively 4% and 7% more than in base case.

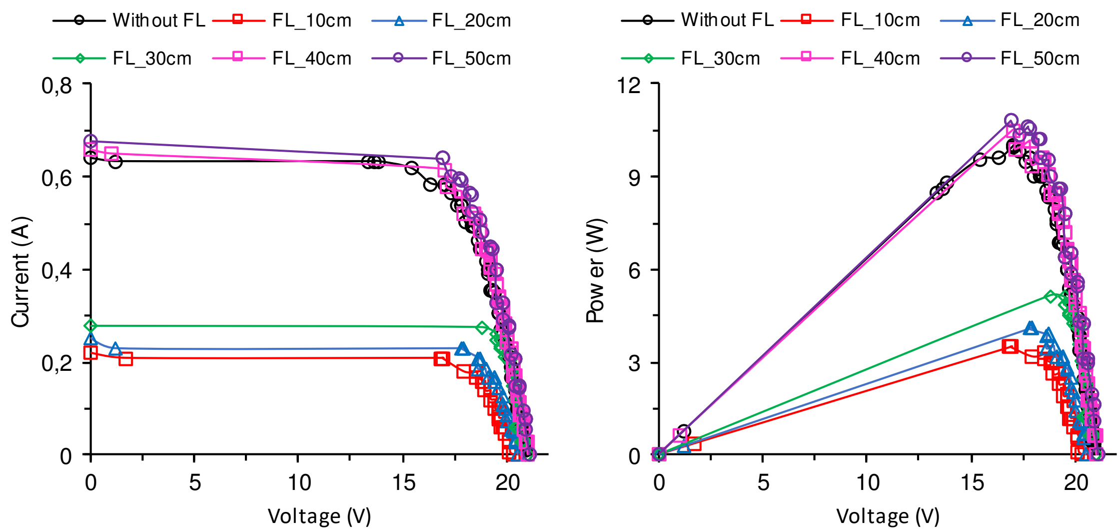

Figure 8. The I-V and P-V characteristics of PV module operating with Fresnel lens

In the case of Fresnel lens placed above the PV module, we can also see an effect of shading of PV module, when concentrating effect does not occur. Once again the highest values of power generation in the PV module were observed, when combination of direct and concentrated sun radiation was affected on the module. This time the direct sun radiation during measurements was lower – from 485 to 505 W/m^2. The I-V and P-V characteristics are presented in Figure 9.

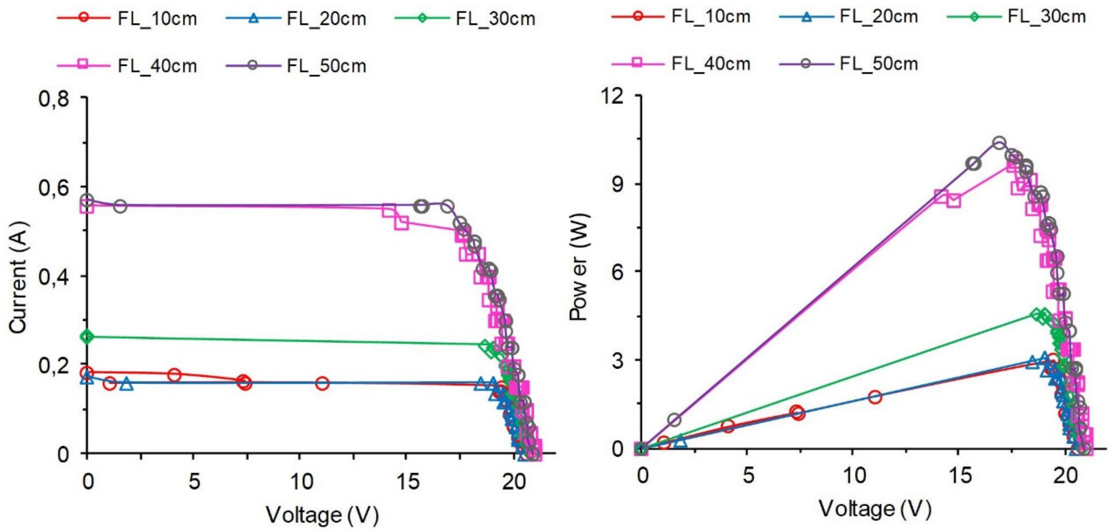

Figure 9. The I-V and P-V characteristics of PV module operating with Fresnel lens (which is placed above the PV module)

The analysis of the data presented in Figure 8 and Figure 9 allows identifying the problem with shading of the PV surface and non-uniform energy flux densities on PV module. To eliminate these problems, an optimal location of Fresnel lens should be found. For example, the series of Fresnel lenses with properly designed spaces between each line may be used. Additionally, each line of Fresnel lenses may be situated with tilt angle suited for the most effective electricity generation in PV module (without or with vertical axis solar tracking). Of course, proposed solutions should be calculated not only for electricity generation but also from the economic point of view.

CONCLUSION

The analysis of the obtained results allows concluding that using Fresnel lens may have a positive effect on the PV module operation. As was shown in TRNSYS simulations, the south-oriented PV module, installed in a vertical position, generates only 10% less electricity in comparison to module with tilt angle from the range of 30-60°. The lower efficiency resulting from the vertical orientation of PV modules may be compensated by the use of solar concentrating system. In the case of tested PV module, its energy performance increased by 7% when Fresnel lens was used. This value will vary for different times of the day and year, so further analysis should be conducted. The next step will be connected with analysis of the onsite operation of a higher number of PV modules integrated with Fresnel lenses. Solar tracking option should be implemented to assess its impact on the performance of the system. On the other hand, Fresnel lenses with better quality should be used to provide more effective sunlight concentration on the PV modules. After collecting results for such configurations, further simulation in TRNSYS may be conducted. Finally, if optimization process and simulations gave positive results, Fresnel lenses might be successfully used in Building-integrated Concentrating Photovoltaic (BICPV) systems.

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