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Efficiency Performance Optimization of Photovoltaic Systems with Solar Concentrators

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ABSTRACT

Solar energy technology has undergone rapid improvement in recent years, with significant increases in efficiency and decreases in cost, solar energy becoming a viable source of renewable energy for both residential and commercial use. However, despite these advancements, the widespread adoption of solar energy as a primary source of power is still hindered by several challenges. One of the major challenges is the intermittency of solar power, which is caused by the dependence on weather conditions and the limited capacity for energy storage. To overcome these challenges, there are several alternative approaches being researched and developed. One promising alternative that should be highlighted is the use of advanced solar concentrators, which use lenses or mirrors to focus sunlight onto small, high-efficiency solar cells to increase the amount of sunlight that reaches the solar panels, thus increasing the system's overall efficiency. Solar concentrators have been widely used in large-scale power plants, they can also be used in residential and commercial applications where the cost of photovoltaic cells is prohibitively expensive. They are especially useful in applications where space is limited or where the goal is to maximize the energy output of a given area. Hence, this study aimed to optimize the output of solar energy systems by using solar concentrators. The performance of the system will be compared under two conditions: one without a solar concentrator and one with solar concentrators. Two types of solar concentrators will be tested, the Fresnel lens and a self-made parabolic dish. The efficiency of the photovoltaic system will be analysed based on the output voltage, current, temperature, and power efficiency. An experiment was conducted, and the results have confirmed the significant improvement in efficiency achieved by using solar concentrators. The highest optimization of efficiency was attained with a self-made parabolic dish, showing an impressive increment of 22.6%, followed by the Fresnel lens with 19.77%, and without any solar concentrator at 17.06%. The data acquisitions further demonstrated the superiority of the parabolic dish over the Fresnel lens and the absence of a solar concentrator.

Keywords:
Solar concentrator; Efficiency optimization; Fresnel lenses; Parabolic dish

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1. Introduction

The photovoltaic solar was first created by French physicist Edmond Becquerel in 1839 [1,2]. It is developed from photovoltaic materials and devices that convert sunlight into electricity and the single PV device is called a battery. The characteristic of a single PV cell is small, normally producing power of around 1 to 2 watts [3]. These cells are produced by made up of different semiconductor materials and the thickness is normally less than the four human hairs. Nowadays, the research and development of solar panels are extensive and applicable without any restrictions. This is because people are undergoing a high technology lifestyle which makes people more convenient to instore electricity through solar panels. Besides that, the material used to make the solar cells are a combination of plastics and glass. In order to boost the power absorption from the sunlight, the cells are connected in a chain and then produce large units of solar cells called solar modules/panels. Most solar panels/modules are framed in aluminium, topped with tempered glass, and sealed by a waterproof backing [4,5]. Unfortunately, depending on the semiconductor material, the efficiency of solar cells is limited to producing high electricity and optical loss [6]. In addition, radiation recombination further limits the possible efficiencies.

In recent years, solar photovoltaics have seen a significant increase in popularity and usage, but the efficiency of traditional photovoltaic panels remains low [7]. This is due to several factors, including the dependence of a photovoltaic cell's output on the constantly changing intensity and position of sunlight, the type and quality of material used, as well as the cost of installation and maintenance. Despite this, the industry has seen substantial growth, thanks to government subsidies and advancements in technology [8-11].

One way to improve solar energy technology is by increasing the efficiency of solar cells. This can be achieved through the use of new materials and techniques, such as the development of perovskite solar cells, which have the potential to surpass traditional silicon-based solar cells in terms of efficiency [7,12-14]. Another way to improve solar energy technology is by reducing the cost of installation and maintenance. This can be achieved through the use of innovative designs and materials, such as the development of flexible and lightweight solar panels, which can be easily installed and maintained. Although solar technology continues to improve, there is still room for further research and development in terms of increasing the efficiency of photovoltaic panels [15-17]. The use of solar concentrators is a promising solution to this challenge and can help to optimize the output of the solar energy system.

In this study, the efficiency of the solar panel by using a concentrator is examined. It is not only applicable to users who want to save their electricity but also beneficial to users do observe the condition of PV panels through smartphones and without using manpower. In addition, it also decreases the risk of an accident [18-21]. This is because the monitoring system of the solar panel is used by a Wi-Fi module based together with other electronic elements which empower the notifications and display of the data.

2. Methodology

This section discusses the concept of enhancing photovoltaic (PV) systems using solar concentrators and the motivation behind employing concentrators to improve energy efficiency. It outlines the design of concentrators considered in concentrating sunlight onto PV cells effectively. Furthermore, the section provides insight into the experimental configuration deployed for the purpose of evaluating the performance of the solar concentrators.

2.1 PV System Enhancement with the Solar Concentrators

Figure 1 shows the system block diagram, categorized into three parts that show the system's overall flow. Firstly, is the PV system part, the three solar panels were set up followed by the Fresnel Lens, and parabolic dish. Besides, the ESP 32 is the microcontroller of this monitoring which controls most of the activity, the power supply is connected to the microcontroller and the whole circuit. The sensors' input is connected to the microcontroller to send the digital input to the microcontroller. Overall, the control part is the monitoring system. Then, the LCD is also controlled by the microcontroller to produce the output values. Lastly, the IoT system was set up as the microcontroller will send the signal to the app Blynk to receive the data by mobile phone.

Then, the sensor input shows the details of the sensor used in the circuit of the solar panel system. The current, temperature and voltage sensor is connected to the microcontroller to send the digital input to the microcontroller. Firstly, the current sensor with the model ACS712 is used to detect the current of the solar panel plant. Next, a temperature sensor, a temperature probe is used to monitor the temperature surrounding the environment of the solar plant. The probe is selected compared to the sensor of LM315 because the maximum heat of the sun is high, the probe will be more suitable used in the circuit to prevent circuit breakdown and withstand the stability of the circuit. Furthermore, the function of the voltage sensor is to detect the current voltage of the solar panel. Besides that, the microcontroller controls the LCD to produce the output values. Lastly, the microcontroller will also transfer the signal to the app Blynk to receive the data when monitoring via mobile phone.

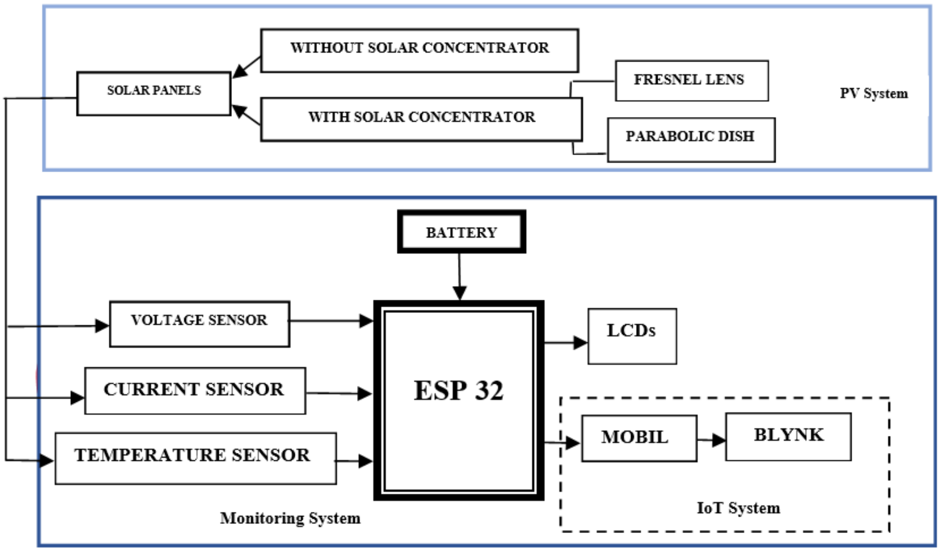

Fig. 1. Block diagram of the proposed solar concentrators enhanced solar system

2.2 Development of Solar Concentrators

The project is going to test under two different conditions such as with and without the solar concentrator. The Fresnel lens is used particularly in lighthouses and searchlights to concentrate the light into a relatively narrow beam. The specification of the Fresnel lens is shown in Table 1.

Table 1
Specification of Fresnel lens

No	Parameter Name	Variable Value
1	Dimensions	0.001m
2	Coating	1.000
3	Operating Temperature	1.0 x 104 (°C)
4	Substrate	-1.0 x 10-4

The parabolic dish comes in with the idea to make it an internal reflection at the back side of the dish. An insulation film is then pasted, fully covering the acrylic surface and contributing to reducing the surrounding temperature. The self-made parabolic dish, as depicted in Figure 2, acts as an optical element, reflecting incident light from all directions through its streamlined side surface and effectively focusing the light on the exit end face.

Fig. 2. Self-made Parabolic dish

The specifications of the parabolic dish are detailed in Table 2. For this study, a window film with a silver-coloured surface was utilized in the self-made parabolic dish to achieve the desired reflecting effect.

Table 2
Specification of Parabolic dish

No	Parameter Name	Variable Value
1	Dimensions	3.0m x 3.0m
2	Effective Focal Length	18.2m
3	Mirror material	reflective film
4	Coating	Uncoated
5	Energy Efficiency	60%

The batteries used along with the solar panels can exhibit variations in both quality and power, resulting in different voltages across manufacturers. A 12-volt solar panel is considered a nominal voltage, typically denoting a solar panel with an open-circuit voltage falling within the range of 18 V to 25 V. The specification of the solar panel can be found Table 3.

Table 3
Specification of solar panel

No	Parameter Name	Variable Value
1	Type of panel	monocrystalline
2	Module type	10W (18.0V)
3	Tolerance	-3%+3%
4	Maximum power, Pmax	10W
5	Open circuit voltage, Voc	21.6V
6	Short circuit current, Isc	0.62A
7	Maximum power current, Imp	0.56A
8	Maximum power voltage, Vmp	18.0V

2.3 Experimental Testing Setup

Figure 3 displays the complete setup of the solar concentrators designed to enhance the performance of the solar panels.

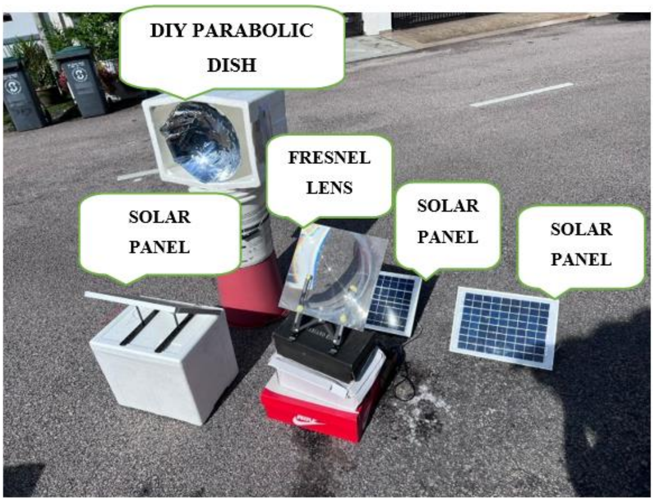

Fig. 3. The complete prototype of the PV system

Figure 4 provides detailed information on the wiring connections within the monitoring system, including the sensors required for this project. The monitoring system has been applied to the solar panel to measure its output parameters, allowing data acquisition via the Blynk application. The data acquisition process was configured to collect data at regular intervals, commencing with hardware setup and subsequently transferring the data from the device to Blynk. The virtual pin data stream is used to transfer the data from connected sensors. Datastream is a channel in Blynk to arrange the data flow through and is independent of hardware. Therefore, the data will be collected in 28 days and recorded every 30 minutes for each PV system.

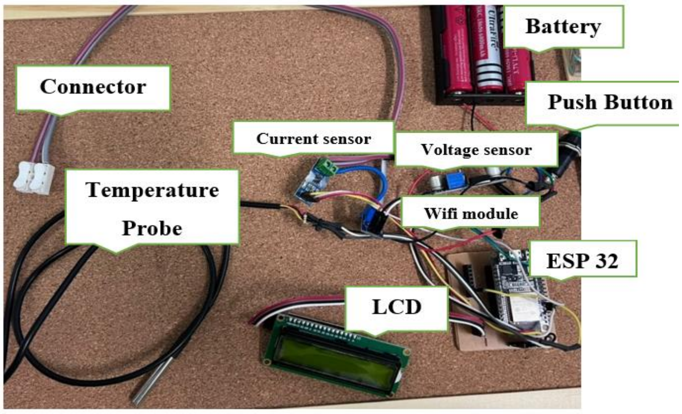

Fig. 4. The complete prototype of the monitoring system

3. Results and Discussion

The experiment was conducted in Taman Bukit Indah, Johor Bahru. All the relevant data were collected from the experiment through DAQ with Blynk. To observe the effect of solar concentrators on the performance of the PV system, The parameters of the output voltage, current, and temperature of the PV panel were observed and recorded separately at regular intervals of 30 minutes using the monitoring system from 9.00 AM to 4.00 PM within a month under three different PV system configurations as follows:

i. Without solar concentrator
ii. With Fresnel lens concentrator
iii. With a self-made parabolic dish concentrator

The experimental configurations were prepared and set at a suitable arrangement so that could attain all the required data within 5 minutes to record for all three arrangements. All the system configurations were set side by side at suitable places and distances at 9 a.m. in order to measure and recorded the output voltage, current, and temperature of the systems. The same procedures were applied to the others two conditions of all the measured data after 30 minutes. Besides, the weather for a month was unstable, and because of the rainy season at the end of the year in Malaysia, the efficiency of the solar system was affected. Even though the effect of climate change, the performance of the PV systems is still under control conditions as shown in Figure 5, Figure 6 and Figure 7. The output values of the parabolic dish concentrator system are greater than the Fresnel lens concentrator and without solar concentrator. Because the insulation film had the function of reducing the surrounding temperature by refracting the light. Thus, the decrease in temperature leads to an increase in the output voltage of the solar panel.

3.1 Data Comparison between the Output of the PV System

Table 4 shows the comparison of the output current of the PV system by 4 weeks. The data was recorded every 30 minutes and data acquisition within 5 minutes of its PV system by the monitoring system.

Table 4
Comparison of the output current of the PV system

Without solar concentrator	With Fresnel lens concentrator	With a parabolic dish concentrator
0.31mA	0.39mA	0.38mA
0.33mA	0.40mA	0.46mA
0.35mA	0.44mA	0.51mA
0.31mA	0.38mA	0.44mA

The PV system's computed average output current and voltage by using the monitoring system on the 28 days from 9 AM to 4 PM with a Fresnel lens concentrator, parabolic dish concentrator, and without a solar concentrator as shown in Figure 5 and Figure 6 respectively. It is observed that the infliction of solar concentrators increases the PV system's output current when the temperature gets higher. In addition, the performance of each concentrator was observed. The highest was a parabolic dish followed by the Fresnel lens and the less efficient was the one without any concentrator each of them with the highest recorded of 0.51mA, 0.44, mA, and 0.35mA respectively.

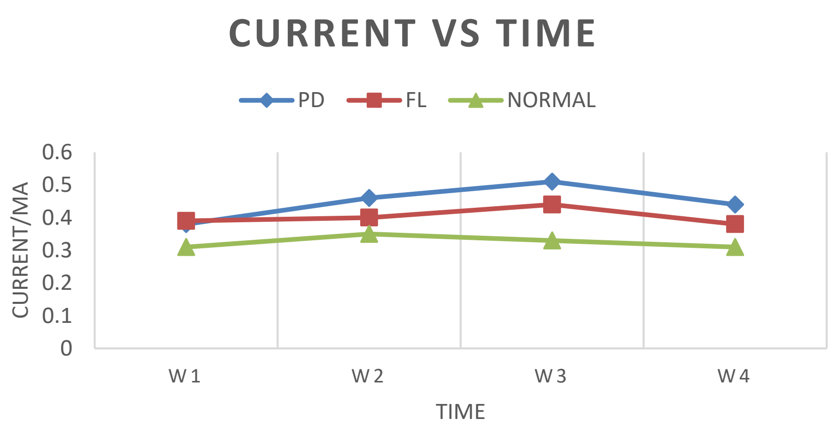

Fig. 5. The comparison of output current in the PV system

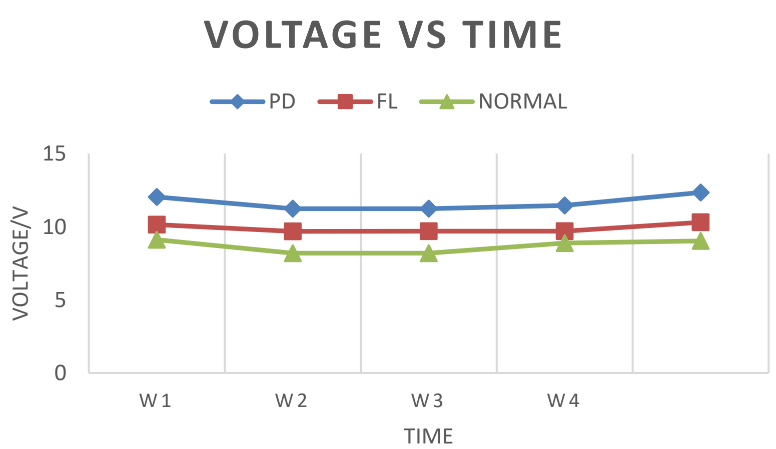

Fig. 6. The comparison of output voltage in the PV system

Table 5 shows the comparison of the output voltage of the PV system. The data was recorded every 30 minutes and data acquisition within 5 minutes of its PV system by the monitoring system. Once again, the performance of each concentrator was a clear gap between them with 12.03V, 10.3V, and 9.11V according to parabolic dish followed by the Fresnel lens and the lesser voltage was the one without any concentrator respectively. It is witnessed that the support of the solar concentrators increases the PV system's output voltage.

Table 5
Comparison of the output current of the PV system

Without solar concentrator	With Fresnel lens concentrator	With a parabolic dish concentrator
9.11V	10.14V	12.03V
8.19V	9.68V	11.23V
8.88V	9.69V	11.45V
9.03V	10.30V	11.34V

3.2 Overall Data Comparison between the PV System

Figure 7 shows the overall data comparison of the output PV system with I-V with the temperature between three solar panels. According to the result shown, as the temperature decrease, the output current will decrease and the output voltage will increase over time. The test was performed to determine the output voltage, current, and temperature through DAQ in Blynk. In addition, the different conditions of the solar panels might be affected by weather too.

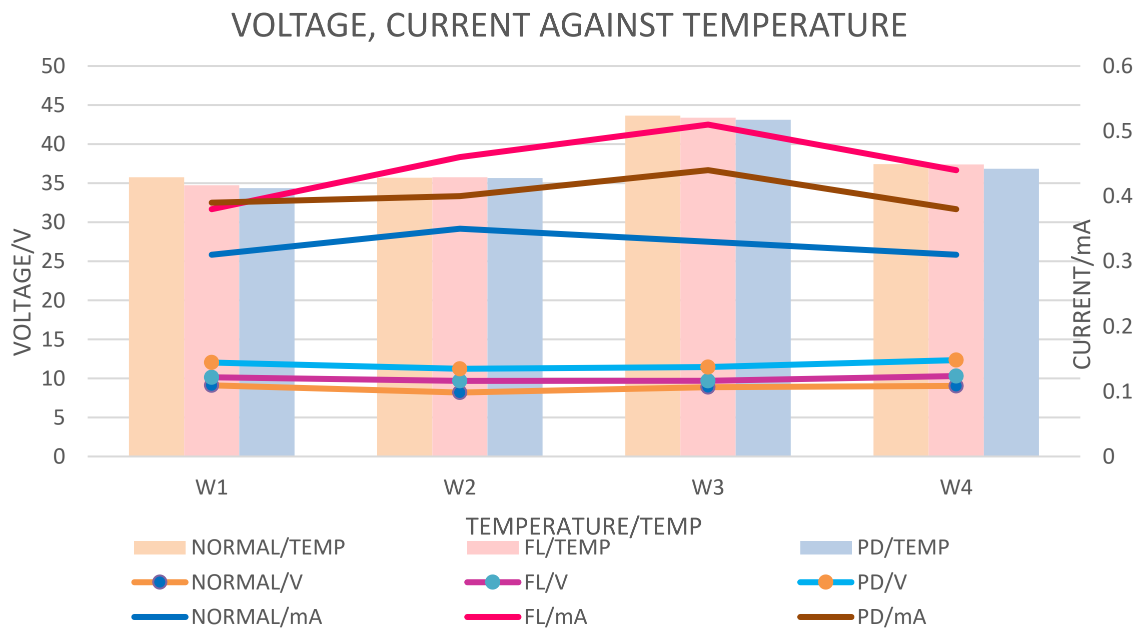

Fig. 7. Comparison of I-V against temperature graph

Firstly, the line shows the current of the three solar panels, the Fresnel lens recorded the highest output current among these. Because the Fresnel lens with the reflecting of light might increase the temperature of the solar panel, thus the output current will also increase. At the same time, the line with makers shows the output voltage of solar panels and the parabolic dish recorded the highest output voltage compare to others. The performance of insulation film has functioned to reduce the temperature of the solar panel when refracting the light to increase the output voltage. Lastly, the clustered column shows the temperature over the month. Climate change at the end of the year affected the performance of PV systems.

Figure 8 shows the output of the P-V graph against temperature. The electrical energy in watts produced by the PV panel will still be the product of voltage times current as in Eq. (1).

$$P = I \; X \; V \tag{1}$$

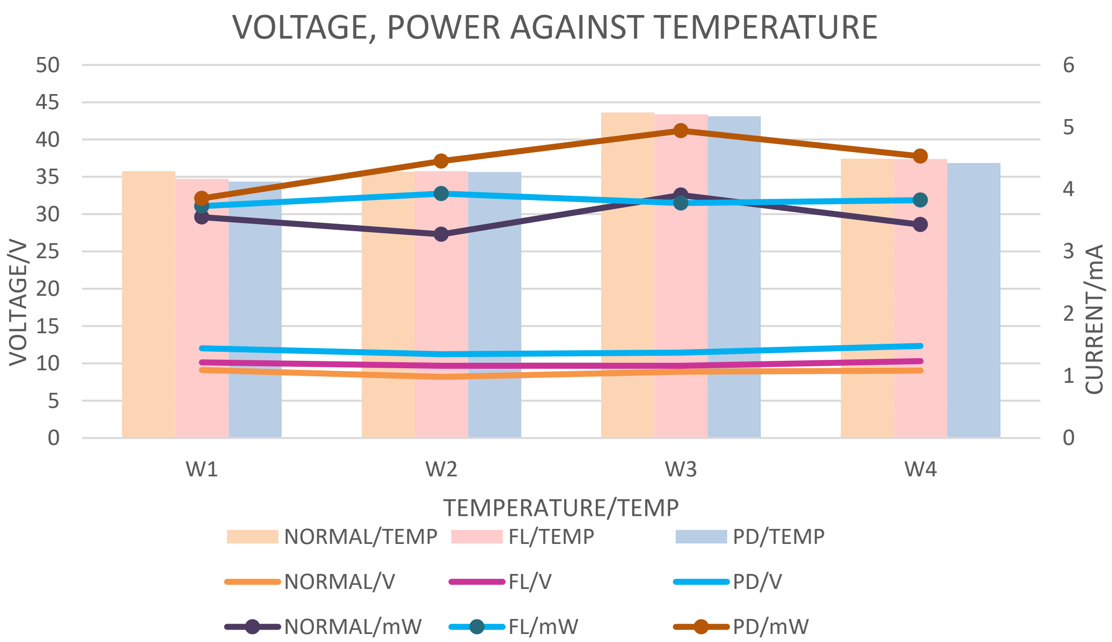

Fig. 8. Comparison of P-V against temperature graph

The overall output power produced by the solar panel without a solar concentrator was the lowest compared to the solar panel with solar concentrators. Because the output power increases when the voltage of the solar panel increase. The result for the solar panel without a solar concentrator was recorded as the lowest output voltage, thus the power will be low. Conversely, the output power of both solar panels with solar concentrators has significantly increased. The two different types of solar concentrators show different increments in output power. Therefore, based on the performance of the output power between the three solar panels shows that the solar panel with a parabolic dish solar concentrator produced a higher output power, followed by the solar panel with a Fresnel lens, and without solar concentrator produced the lowest output power. The power of the output solar panel was calculated using the formula specified in Eq. (1).

3.3 Effectiveness of Solar Concentrators

In order to analyse the efficiency of the solar panel under different conditions to enhance the performance of PV systems. The calculation of the output power and efficiency of the solar panels was completed by using Eq. (1) to Eq. (4). As shown in Table 6, the application of the parabolic dish has the highest output power followed by a Fresnel lens without using a concentrator.

$$MPP \;=\; Imp \; x \; Vmp \tag{2}$$

$$FF \;=\; MPP \,/\, Voc \; x \; Isc \tag{3}$$

$$\eta = FF \, x \, Voc \, x \, Isc \, / \, Pin \quad (4)$$

Table 6
Comparison of the output current of the PV system

Parameter	Without solar concentrator	With Fresnel lens concentrator	With a parabolic dish concentrator
Average Power, mW	2.90	3.98	5.79
Efficiency, %	17.06	19.77	22.60

4. Conclusions

The main objective of this study was to explore the potential power optimization of photovoltaic systems using solar concentrators, and the results were encouraging. Based on the experimental results, the implementation of solar concentrators, specifically the Fresnel lens and the self-made parabolic dish, proved to be highly effective in significantly improving the efficiency of the PV system. The Fresnel lens demonstrated an impressive 19.77% increase in output power, while the self-made parabolic dish achieved an even higher improvement of 22.60% during the month-long observation period facilitated by the IoT monitoring system. In summary, the findings confirmed the utilizing of solar concentrators, particularly the Fresnel lens and the self-made parabolic dish, which can be a practical and promising approach for enhancing the efficiency of photovoltaic systems. Overall, solar concentrators are relatively simple and inexpensive compared with other alternatives, and they offer a wide range of potential applications.

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