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An Experimental Study of Concentrator Photovoltaic Thermoelectric Generator with Different Concentrator Positions Using Real-Time IoT Monitoring

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Abstract

This project addresses the increasing need for efficient renewable energy by introducing a Concentrated Hybrid Photovoltaic-Thermoelectric (CPV-TE) system with integrated Internet of Things (IoT) monitoring. It aims to create a system that efficiently harnesses energy from sunlight and temperature changes by leveraging concentrated photovoltaic (CPV) technology and thermoelectric (TE) energy harvesting. The study adjusts the distance between the Fresnel lens and solar panel to match the focal length and collects data from 11 a.m. to 4 p.m. across four different Fresnel lens positions. Results indicate that while a 16.5 cm spacing initially showed potential for higher output, longer-term performance revealed other influencing factors. Overall, the Fresnel lens improved voltage and power outputs but highlighted the complexity of optimizing solar energy systems. This investigation thoroughly explores CPV-TE system dynamics and emphasizes the importance of considering solar coverage, temperature changes, and complementary technologies for effective and sustained renewable energy harvesting.

1. Introduction

In recent times, the demand for better and sustainable energy solutions, especially for remote areas, has increased. To improve energy collection, researchers have explored combining different technologies [1-5]. One method involves combining thermoelectric (TE) energy collection with photovoltaic (PV) systems, resulting in a hybrid photovoltaic-thermoelectric (PV-TE) system. This hybrid system uses waste heat to generate extra electricity alongside solar power from PV systems. In the landscape of concentrated CPV-TE hybrid systems, there is an apparent need exists in the specific area of the project. While previous research has focused on the efficiency, topologies, and viability of CPV-TE systems [6-15], there has been little attention paid to the effect of Fresnel lens distance on solar panel integrated with thermoelectric power generation in conjunction with real-time data monitoring via the Internet ofThings (IoT).

This project integrates CPV-TE technology with IoT in an innovative way, utilising Arduino and ThingSpeak to provide ongoing and precise monitoring. The comprehensive investigation of various Fresnel lens distances and their impact on solar panel power generation is the distinguishing feature. This adds an important layer to understanding CPV-TE systems, as environmental factors such as the distance of the Fresnel lens play a critical part in determining the system's efficiency and overall performance. ThingSpeak's continuous monitoring of data at minute-by-minute intervals provides a real-time perspective. Furthermore, the incorporation of IoT in the form of Arduino and ThingSpeak represents a contribution not only to the fundamental understanding of CPV-TE systems, but also to the practical considerations and technological advancements required for the future development of efficient and adaptive solar energy solutions.

This project's aim to design a CPV-TEG energy harvesting system that can efficiently harvest energy from both sunlight and temperature differences and real-time monitoring using IoT. The output of CPV-TEG in four cases that have differents position of Fresnel lens and in two differents duration for each case were compared and analyzed. Several major features are included in the project to design and execute a concentrated hybrid photovoltaic thermoelectric energy harvesting system. The scope covers the strategic usage of a 30 cm x 30 cm Fresnel lens as a solar concentrator to improve solar energy capture. Six Thermoelectric Generator (TEG) modules are joined in series with the PV panel to provide optimal coverage of the solar panel area when the system is configured. The integration of a 5V output solar panel fits with the project's aims, and four various distances (0 cm, 16.5 cm, 33 cm, and 66 cm) are established between the Fresnel lens and the solar panel to optimise solar concentration. The implementation of ThingSpeak, which collects critical metrics such as PV output voltage, TEG output voltage, temperature gradients, and short-circuit current, allows for real-time monitoring. Additionally, ThingView is integrated to facilitate convenient data monitoring through smartphones, ensuring accessibility. The ESP32 microcontroller is used for overall system control, data gathering, communication, and reliability. This stated scope provides a solid foundation for the concentrated hybrid energy harvesting system's systematic development and evaluation.

2. Methodology

2.1 The development of a CPV-TEG hybrid system

Fig. 1 shows the project's development from start to finish. The approach begins with the development of a hybrid CPV-TEG system, which be used to investigate various Fresnel lens distances onto a solar panel. Four distinct are explored, each with a different distance between the Fresnel lens and the solar panel. Case 1 investigates at the circumstances where the Fresnel lens is positioned at 0 cm onto the solar panel, Case 2 at 16.5 cm, Case 3 at 33 cm, and Case 4 at 66 cm. Afterwards, the system implements the IoT paradigm, utilising sensors for comprehensive monitoring via the ThingSpeak platform. This IoT integration enables real-time data collecting and analysis.

If the output fits the criteria, the system moves on to data collecting, which includes crucial characteristics such as solar irradiance, temperature, output voltage, and output current. This data provides useful insights into the system's performance at various Fresnel lens distances. Finally, the procedure closes, indicating that data collection and analysis for the given cases has been completed. This method ensures a thorough investigation of the hybrid CPV-TEG system's behaviour, providing vital information for further optimisation and comprehension. The main materials that are used in this project is solar cells.

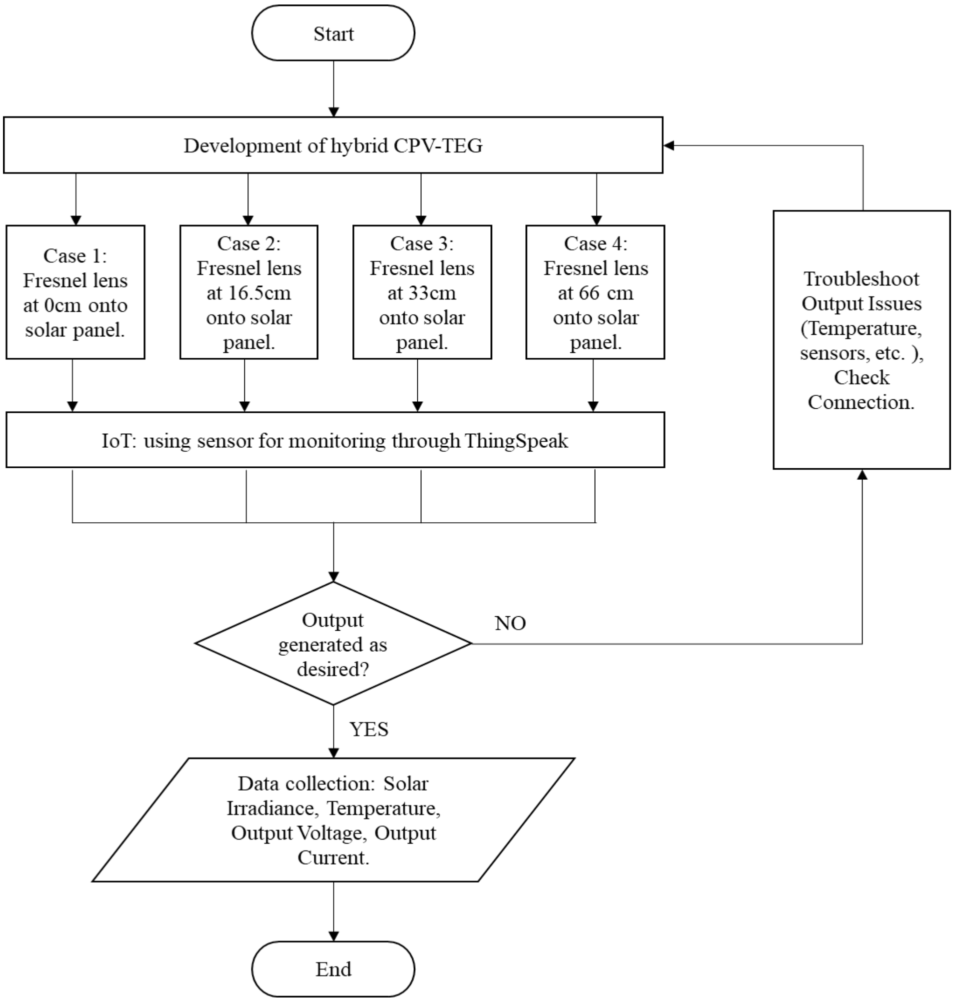

Fig. 1 *Flowchart of the process.*

2.2 The flow of the coding system that integrate on ESP32 through Arduino IDE software

Fig. 2 shows the flowchart of the coding system. The programme initiates execution by connecting to a predetermined WiFi network using predefined credentials. Upon successful connection, different sensors are initialised, including DHT sensors for analog-to-digital conversion. Temperature readings from the DHT sensors are collected, and default values are assigned when readings are unavailable. Analogue voltage samples are then gathered from different pins for subsequent calculations. The temperature gradient is calculated using the recorded temperature values and different coefficients for different temperature ranges. Following that, current and voltage values are calculated using the temperature gradients and voltage samples. The sensor data, which include current, voltage, and temperature, are presented on the Serial Monitor for debugging and monitoring. Simultaneously, the system transmits these estimated sensor values to ThingSpeak via the ThingSpeak API, including currents, voltages, and temperature gradients. If the transmission is successful, a confirmation message is sent; otherwise, an error message is sent. Following a 15-second wait, the programme iterates through this process, ensuring a controlled sampling rate. This loop continues until manually terminated or an error in the program's execution occurs.

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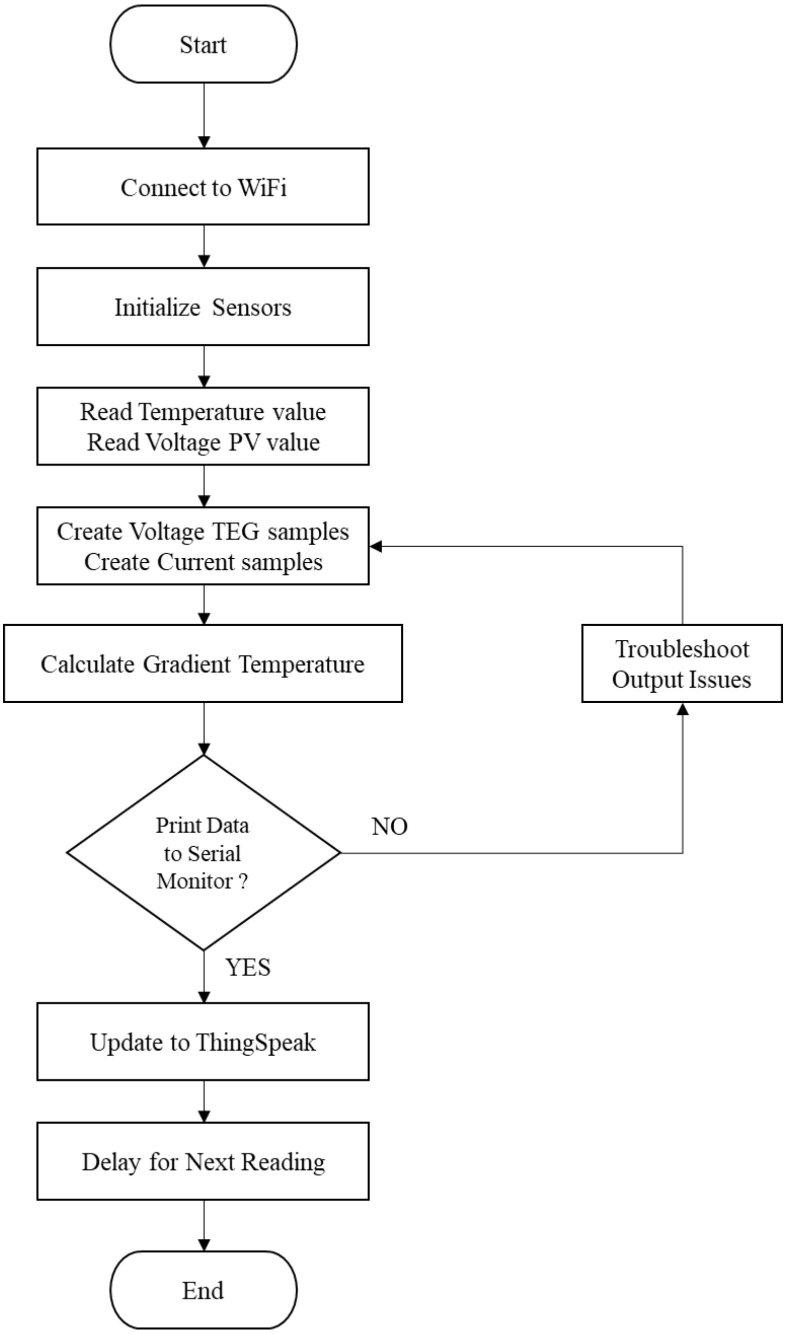
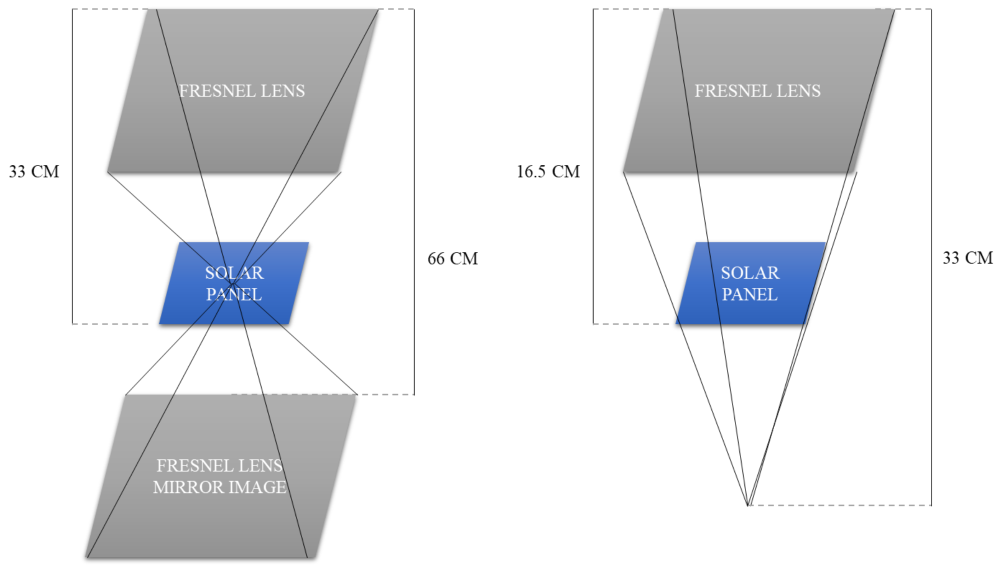


Fig. 2 *Flowchart of the coding system*

2.3 Experimental Setup

This experiment is inspired by Mohaimin et al [16], aiming to enhance solar energy capture by adding a 30 cm by 30 cm Fresnel lens, situated 33 cm away from a 16.5 cm by 13.3 cm solar panel, both tilted at a fixed 30-degree angle. Two solar panels, one with a lens and one without, will each have six TEG modules connected in series to optimize heat usage. The experiment runs from 11 a.m. to 4 p.m., adjusting the distance between the Fresnel lens and the solar panel according to its focal length, measured with a tape measure. Four scenarios are tested over four days: Case 1 (Fresnel lens at 0 cm), Case 2 (Fresnel lens at 16.5 cm), Case 3 (Fresnel lens at 33 cm), and Case 4 (Fresnel lens at 66 cm). Fig. 3 shows the Fresnel lens positions. Data is collected using ThingSpeak, recording various parameters, except ambient temperature and irradiance, which are manually measured. This setup aims to understand how Fresnel lens distance affects solar panel performance and energy generation by optimizing light precision and utilizing excess heat to power a TEG.



(a) (b)

Fig. 3 *(a) Fresnel lens at 33 cm from solar panel, focal length of Fresnel lens is at 33 cm and 66 cm; (b) Fresnel lens at 16.5 cm from solar panel. At 16.5 cm position, sunlight covers all surface area of solar panel*

The experimental setup includes two separate systems, one with and one without a concentrator. The ESP32 microcontroller is used in both systems for seamless integration and efficient data transmission. A voltage sensor, an ACS721 current sensor, and a DHT22 temperature sensor are among the key sensors included. Fig. 4 depicts the connection for the sensor. The arrangement in System 1 with a concentrator includes one voltage sensor for measuring the voltage output of the solar panel, another for measuring the output of the TEG, a current sensor for gathering the output current, and two temperature sensors bound to monitoring the solar panel and the cooling mechanism. System 2, the counterpart without a concentrator, has the same component configuration as System 1. Fig. 5 shows the arrangement of system 1 and system 2 on esp32. Sensor connections are methodically constructed in both systems to ensure reliable data collecting. This data is then communicated to ThingSpeak, where it is visualised graphically and saved for later analysis. Furthermore, the data may be easily monitored using ThingView, which provides a full and easily accessible overview of the experiment's electronic components and how it performs in both concentrator and non-concentrator scenarios.

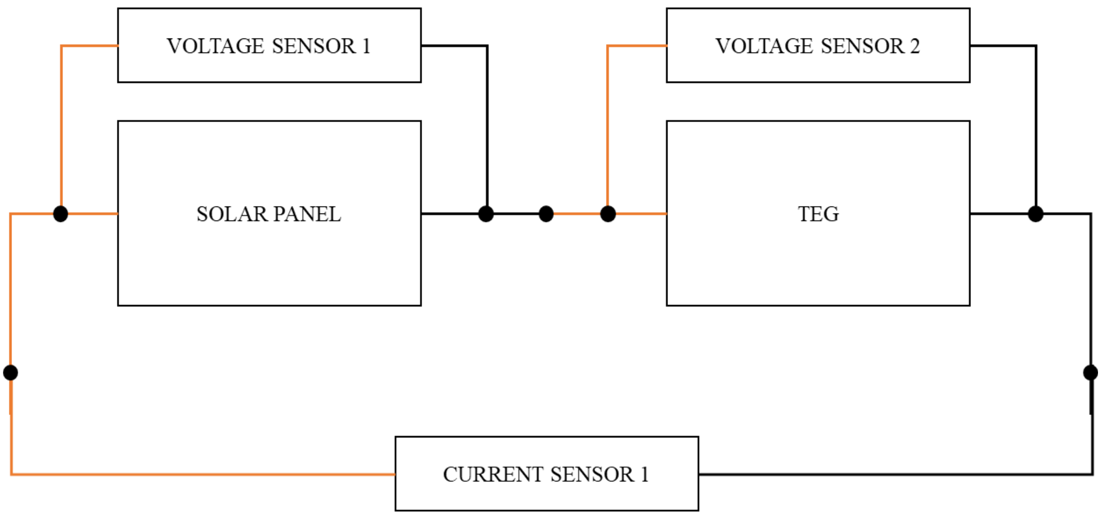


Fig. 4 *The connection for the sensor*

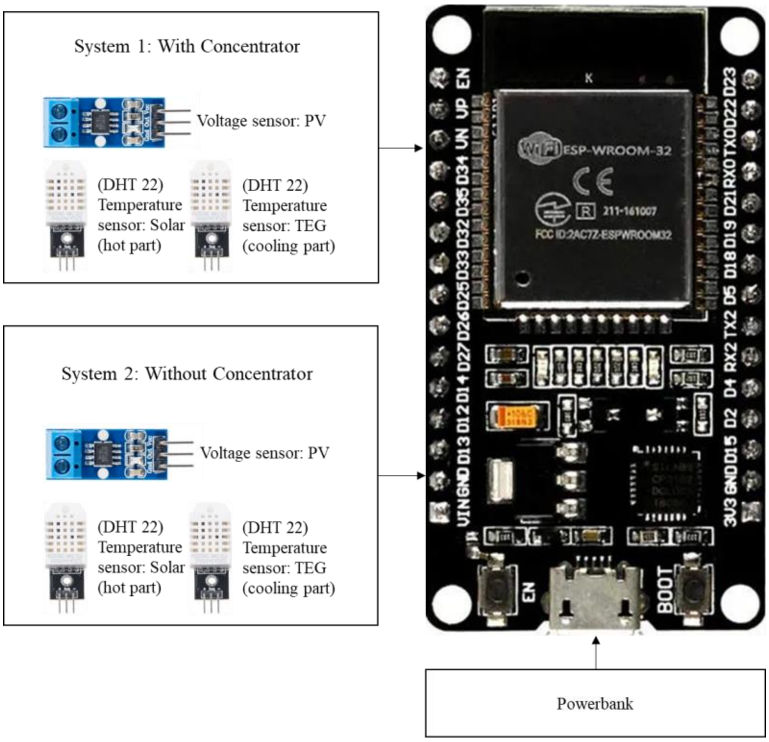


Fig 5 *The arrangement of system 1 and system 2 on esp32.*

3. Result and discussion

The outcomes and discussions obtained from two sets of experiments involving CPV-TEG. The first set concentrates on the CPV-TEG's voltage output in specific instances across four different cases. These cases involve positioning the Fresnel lens at specific distances; directly on the solar panel (0 cm), covering the entire panel (16.5 cm), positioned at the focal length (33 cm), and twice the focal length (66 cm). Conversely, the second set focuses on evaluating the CPV-TEG's performance over a prolonged duration of 5 hours under similar Fresnel lens positioning conditions. The intention behind these experiments is to deeply explore how the CPV-TEG operates and performs under varying Fresnel lens placements, providing understanding into its short-term and long-term efficiency characteristics. Through these investigations, the aim is to clarify the impact of Fresnel lens positions on the CPV-TEG's functionality and effectiveness, shedding light on its behavior in both immediate and extended periods, thereby contributing to a comprehensive understanding of its performance in practical applications.

3.1 Short-duration (instance) Performance of CPV-TEG for Different Location of Fresnel lens

The primary aim of the initial experiment was to determine the best position for the Fresnel lens above the solar panel, resulting in the highest voltage generation. This experiment was conducted at noon, specifically when the sun reaches its highest point and emits the strongest light of the day. At this time, the Fresnel lens is positioned most directly facing the sun, concentrating and intensifying light onto the solar panel. The voltage outcomes obtained from this experiment are displayed in Table 1.

Table 1 *The instantaneous voltage results*

Experiment condition	Output voltage without Fresnel lens (V)	Output voltage with Fresnel lens (V) .	Voltage output change with Fresnel lens (%) = [(with – without)/without] x 100%
Case 1: Fresnel lens at 0 cm, resting on solar panel	6.16	5.89	-4.38

Case 2: Fresnel lens at 16.5 cm, covering all areas of solar panel	5.87	5.92	0.85
Case 3: Fresnel lens at 33 cm, at focal length	5.85	5.70	-2.56
Case 4: Fresnel lens at 66 cm, at double focal length	6.19	5.78	-6.62

The investigation focused on evaluating the influence of different positions of the Fresnel lens on top of solar panel affected the voltage output. Four different cases were examined. Case 1 involved the lens placed at 0 cm, directly resting on the panel, resulting in a decrease of 4.38% in voltage output, likely due to potential shading effects caused by the lens obstructing sunlight to some panel areas. Case 2, where the sunlight covered the entire panel surface at 16.5 cm, displayed a positive change in voltage output of 0.85%, indicating efficient sunlight concentration without significant shading. In Case 3, positioning the lens at 33 cm, corresponding to the focal length, resulted in a 2.56% decrease in voltage output. This occurs because the sunlight gets concentrated into a small area, causing shading of the surrounding active area by the Fresnel lens. Case 4, placing the lens at 66 cm (twice the focal length), led to a substantial decrease in voltage output by 6.62%, indicating increased shading and reduced overall voltage generation. Overall, optimal voltage generation appears when the sunlight covers the entire panel, minimizing shading effects, while direct placement on the panel or positioning beyond the focal length induces shading, diminishing voltage output.

3.2 Performance of CPV-TEG for long term duration for Case 1

Fig. 6 displays the setup with the Fresnel lens positioned at a distance of 0 cm, resting directly on the solar panel. In Fig. 7, the graphs illustrate the measured total voltage output and current when the Fresnel lens is positioned 0 cm above the panel at a 30° angle. The left side of the graph (y-axis) represents the total output voltage, while the right side (y-axis) represents the output current. The x-axis denotes time in a 24-hour format. The observation from these graphs indicates that the voltage outputs from both the solar panel configurations (with and without the Fresnel lens) were almost identical. However, the output current generated by the PV-TEG system with the Fresnel lens positioned at 0 cm above the panel is greater in comparison to the current generated by the PV-TEG system without the Fresnel lens.

Fig. 6 *The setup for Fresnel lens distance at 0 cm on the solar panel*

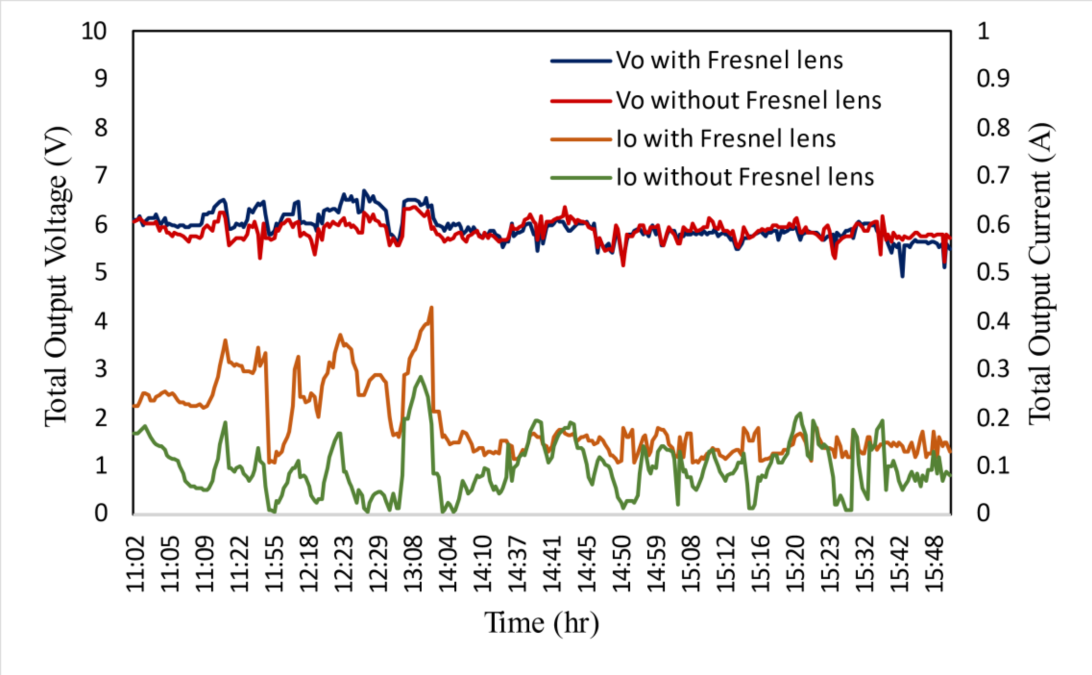


Fig. 7 *The total voltage output and output current measured for case 1*

Fig. 8 shows the total output power(W) for case 1. It shows that the output power for PV-TEG with Fresnel lens rested on top of panel is higher than without lens when the experiment conducted for a long duration. This result is contradicting the instantaneous experiment conducted at one time where the PV-TEG with Fresnel lens produce lower output compared to PV-TEG with lens.

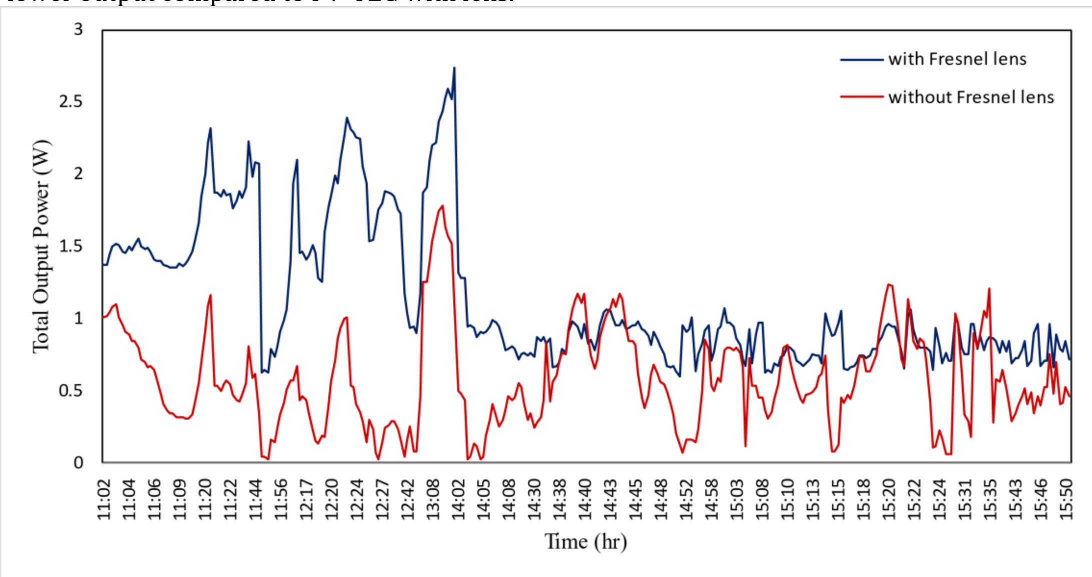


Fig. 8 *The total output power (W) for case 1*

Despite analyzing the results for total voltage, current, and power (which combines PV and TEG), examining the individual contributions of standalone PV and TEG is also crucial. This analysis helps to determine the specific contributions of PV and TEG towards generating the output voltage. The output voltage for PV without Fresnel lens is slightly greater than PV output voltage with Fresnel lens. But for TEG, the output voltage with Fresnel lens is higher than without Fresnel lens. The relationship between temperature gradient and output voltage of TEG confirms the fundamental concept of Seebeck's effect. The gradient temperature is higher in the early hours, resulting in a larger difference between output voltage with and without Fresnel lens. The gradient temperature, however, lowers as the day passes until the afternoon. This decrease is linked to a minor cooling impact, most likely caused by insufficient cooling system temperature. For case 1, it can be concluded that the contribution from the TEG significantly influences the overall performance enhancement of the CPV-TEG system.

3.3 Performance of CPV-TEG for long term duration for Case 2

Fig. 9 shows the setup when Fresnel lens at distance 16.5 cm above the solar panel. Fig. 10 depicts the total output voltage and current measured when Fresnel lens at 16.5 cm above the panel and angle for 30° and without the Fresnel lens. The left side of the graph (y-axis) represents the total output voltage, while the right side (y-axis) represents the output current. The x-axis denotes time in a 24-hour format.

Fig. 9 *The setup for Fresnel lens distance at 16.5 cm above solar panel*

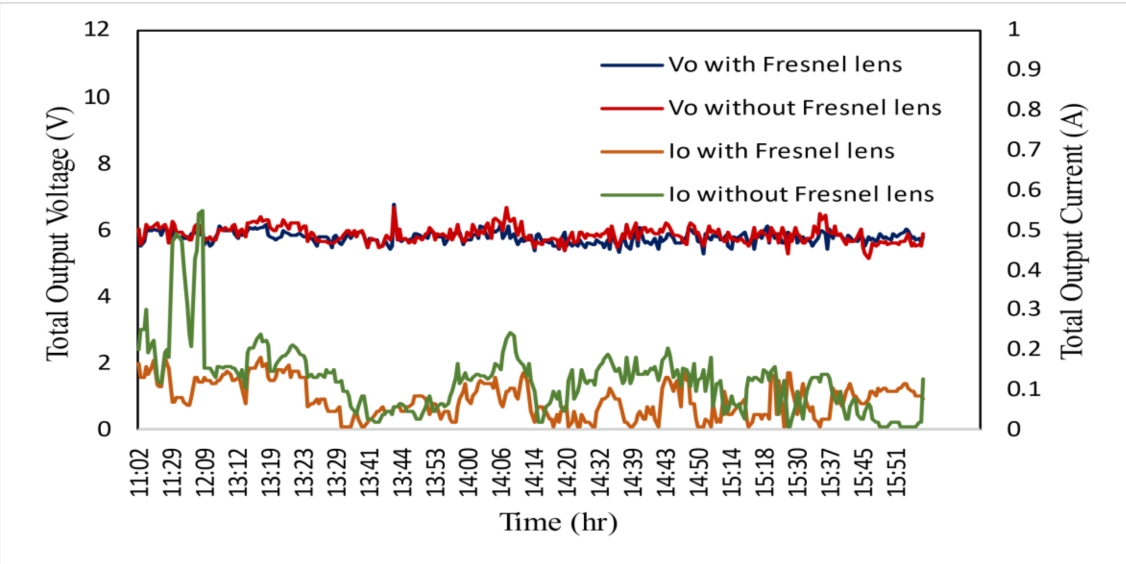


Fig. 10 *The total voltage output and current short circuit measured for case 2*

Fig. 11 shows the total output power for case 2. For this case, where the sunlight covered the entire surface of the solar panel as in short duration experiment in section 4.2, unexpected reductions in the PV-TEG system's performance were observed. Despite expectations for an increase in efficiency, the outcomes revealed a decrease in total current, voltage, and power readings for the PV-TEG system with the Fresnel lens compared to the system without lens. Over time, the dynamic nature of sunlight might have caused varying conditions, intermittently allowing optimal coverage and then causing shadows, ultimately affecting the system's efficiency and resulting in reduced voltage output.

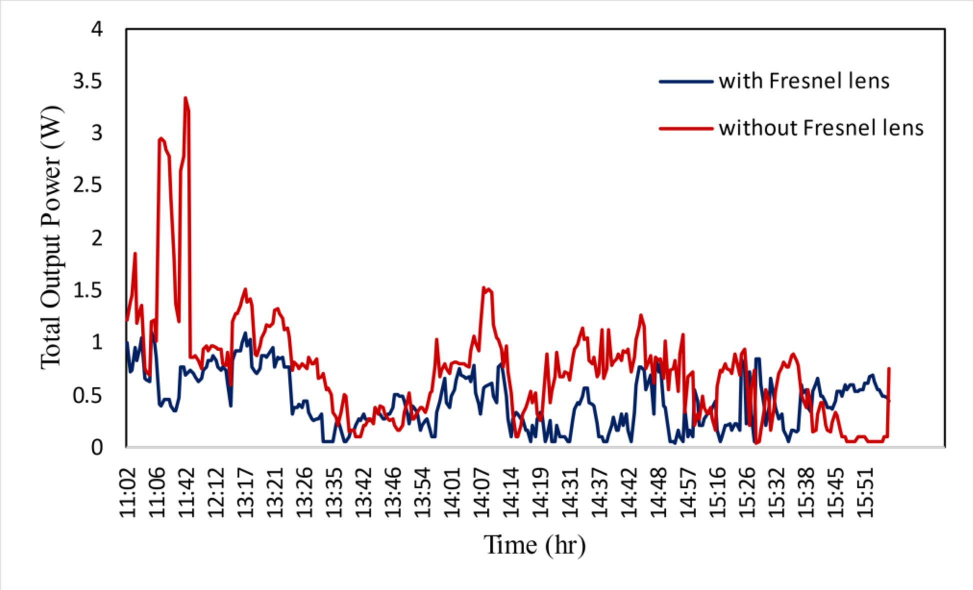


Fig. 11 *The total power output (W) when Fresnel lens for case 2*

The voltage difference between with and without Fresnel lens is almost identical. This implies that the PV output voltage does not contribute to the overall performance of CPV-TEG for case 2. Also, the irradiance does not affect the production of PV output voltage. This might be due to some reasons and factors. TEG output voltage most contributes to the overall performance of CPV-TEG. The TEG output voltage decreases when PV-TEG is installed with Fresnel lens 16.5 cm above solar panel compared to PV-TEG without Fresnel lens. The reason might be due to the presence of Fresnel lens 16.5 cm above the solar panel. As discussed previously, the Fresnel lens in case 2 provides a shadow for solar panel due to the dynamic nature of sunlight. This shadow prevents the solar panel from heating up. Thus, the temperature gradient for PV-TEG with Fresnel lens is lower than PV-TEG without Fresnel lens.

3.4 Performance of CPV-TEG for long term duration for Case 3

Fig. 12 shows the setup when Fresnel lens at distance 33 cm. The focal length of the Fresnel lens concentrates all the solar panel's irradiance into a single area in the centre. However, after a few seconds, the film layer of the solar panel began to melt due to the extremely high heat, but because the solar panel has tempered glass, the solar panel state remains stable. At 12 p.m., the light's focus point had moved to the outside range of the solar panel. Fig. 13 depicts the total output voltage and current measured when Fresnel lens at 33cm above the panel and angle for 30°. Left y-axis represent total output voltage and right y-axis represent current short circuit for the system. x-axis shows the time in 24-hour system.

Fig. 12 *The setup for Fresnel lens distance at 33 cm above solar panel*

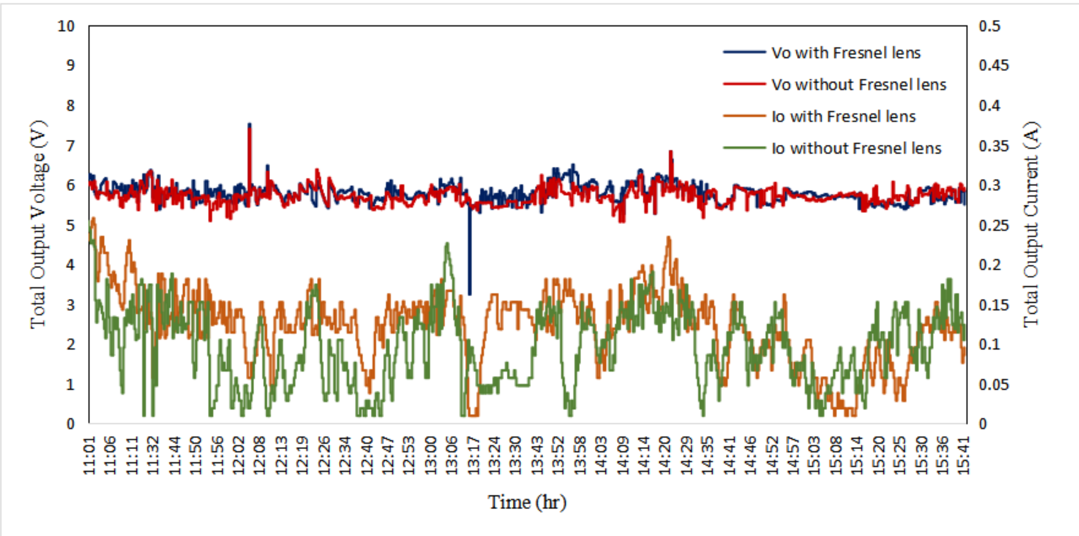


Fig. 13 *The total voltage output and current short circuit measured for case 3*

Fig. 14 shows total output power (W) when Fresnel lens at 33 cm above the solar panel. The gap between with and without for total power output seems become closer because of the lack of focus point from the sunlight.

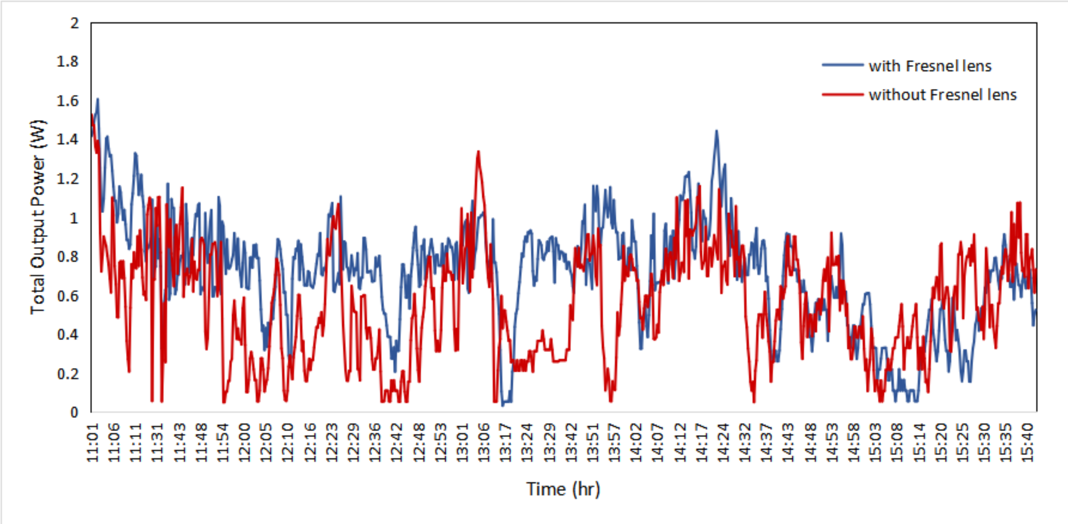


Fig.14 *The total power output (W) when Fresnel lens for case 3*

The difference in voltage between with and without Fresnel lens is clearly not significant for PV, but an interesting trend emerges. Surprisingly, despite the favorable effect of the Fresnel lens, output voltage without Fresnel lens regularly has greater values than output voltage with Fresnel lens. The focus of light on a specific spot caused by the Fresnel lens is known as observation. Initially, the solar panel produces good output with the lens in place during the early portion of the day. As the distance between the lines indicating voltage TEG output with Fresnel lens and voltage output without Fresnel lens become closer pattern. This pattern illustrate, in Case 3, the Fresnel lens impacts make reducing the difference between TEG voltage outputs with Fresnel lens and without the lens. The shrinking gap represents the effect of the Fresnel lens on the TEG system. It also depicts the correlation between gradient temperature and TEG output. The temperature gradient lines follow a pattern that corresponds to the theoretical understanding of TEG. The impact of the Fresnel lens focusing light on a specific location on the solar panel is an important observation. This concentration is most likely contributing to the ongoing narrowing of the gap between voltage output with and without Fresnel lens The concentrated light improves the heating effect, increasing the TEG output.

3.5 Performance of CPV-TEG for long term duration for Case 4

Fig. 15 shows the setup when Fresnel lens at distance 66 cm. Irradiance has exceeded the focal length and is now equal to the distance to the Fresnel lens's mirror image at 66 cm. Irradiance illuminates the solar panel as well as the surrounding area but reversed. Voltage output from solar panel with Fresnel lens is lower from without the Fresnel lens. Fig. 16 depicts the total output voltage and current measured when Fresnel lens at 66 cm above the panel and angle for 30°. Left y-axis represent total output voltage and right y-axis represent current short circuit for the system. X-axis shows the time in 24-hour system.

Fig. 15 *The setup for distance at 66 cm*

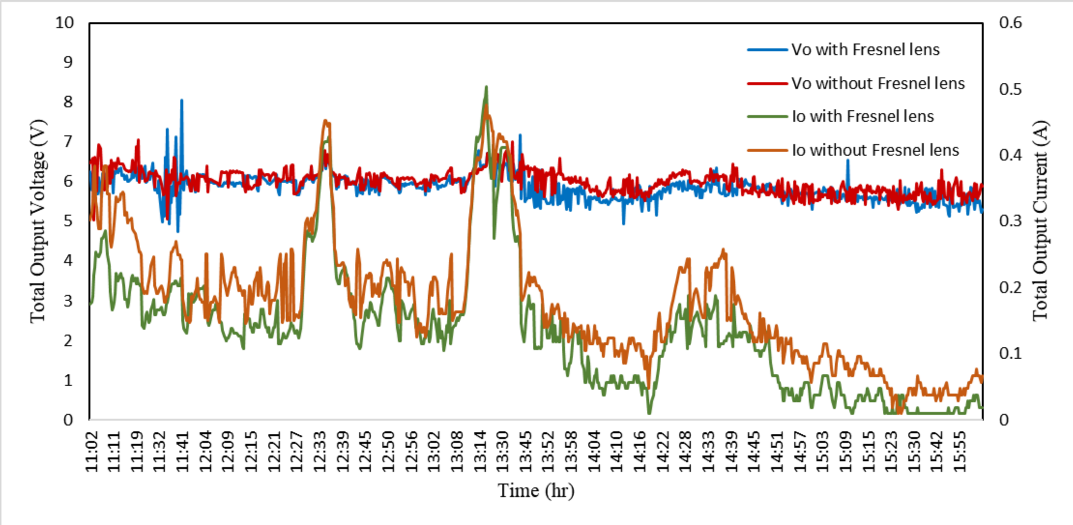


Fig. 16 *The total voltage output and current short circuit measured for case 4*

Fig. 17 shows total power output (W) when Fresnel lens at 33 cm above the solar panel. Fresnel lens is resting on top of solar panel with angle 30°. The y-axis represents for total power output of the system with and without the Fresnel lens. The x-axis represents for time in 24-hour system.

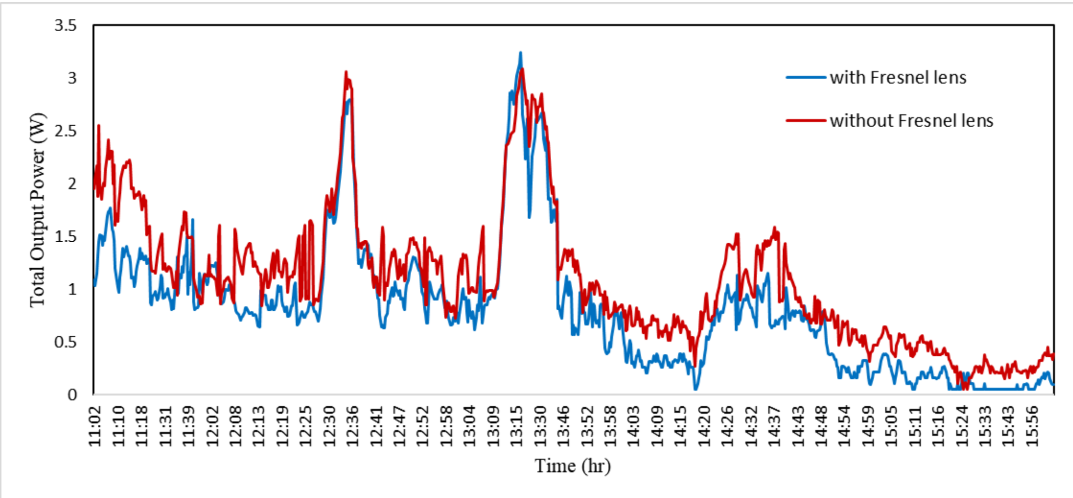


Fig. 17 *The total power output (W) when Fresnel lens for case 4.*

The voltage difference between voltage output PV with and without a Fresnel lens is not significant. Throughout the observation period, voltage output without Fresnel lens constantly exhibits greater values than voltage with Fresnel lens. Despite the good influence of irradiance, the pattern implies that the distance of 66 cm may not be optimising the Fresnel lens's benefits. When the lens is in place, the lights focused on the solar panel seem fuzzy, potentially decreasing the efficiency of light absorption and resulting in a lower voltage output. When the space between the lines indicating voltage output TEG with Fresnel lens and voltage output without Fresnel lens is steadily reduced, a noticeable trend appears. In Case 4, the Fresnel lens impacts become reducing the difference between TEG outputs with and without the lens. The effect of the Fresnel lens's fuzzy focus on the solar panel is an important observation. This blurriness is most likely contributing to the observed decrease in TEG output. The less focused and diffused light reduces the heating effect on the solar panel, resulting in a lesser temperature gradient and, as a result, reduced TEG output.

3.5 Comparison performance of CPV-TEG for different location of Fresnel lens

This section evaluated the effect of utilising a Fresnel lens at various distances on experimental data, taking into account four separate circumstances. Table 2 shows the comparison of average voltage, current and power for every case and Fig. 18 shows the illustration of the comparison.

Table 2 *The comparison for every cases*

	Case 1		**Case 2**		**Case 3**		**Case 4**	
	without Fresnel lens	with Fresnel lens	without Fresnel lens	with Fresnel lens	without Fresnel lens	with Fresnel lens	without Fresnel lens	with Fresnel lens
Average Voltage (V)	5.876	5.947	5.871	5.781	5.714	5.780	5.992	5.854
Average Current (A)	0.097	0.189	0.127	0.077	0.096	0.122	0.179	0.135
Average Power (W)	0.578	1.138	0.754	0.448	0.555	0.711	1.091	0.815

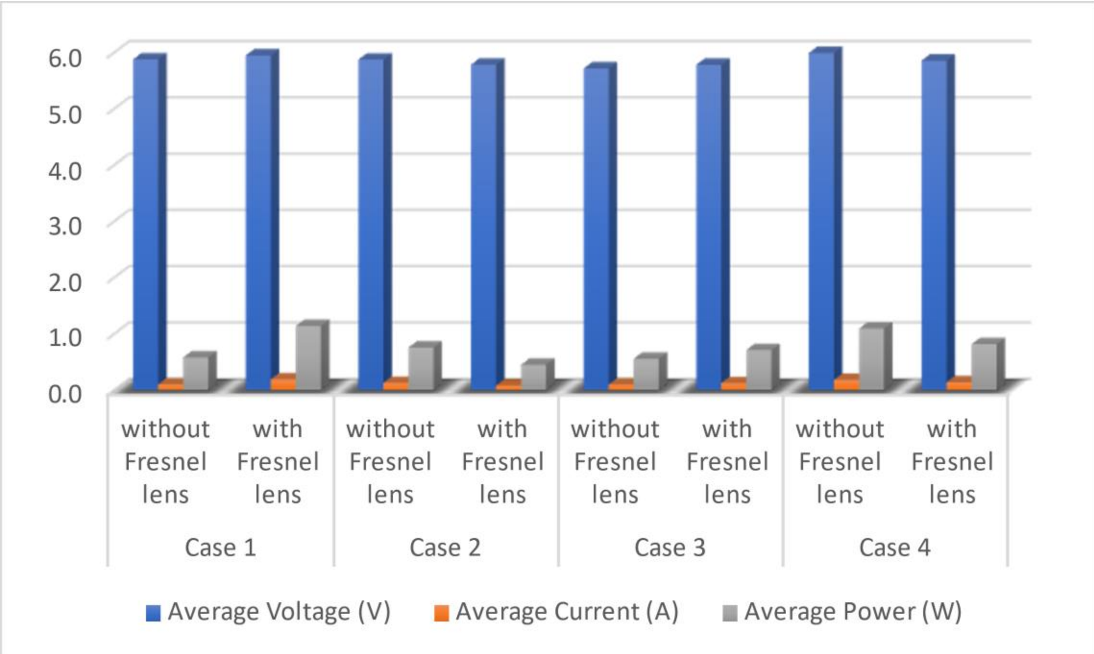


Fig. 18 *The illustration of comparison for every cases*

The study produced several important discoveries into using Fresnel lenses at different distances in solar energy setups. Placing the Fresnel lens at 16.5 cm appeared promising initially, ensuring sunlight covered the entire active area of the solar panel, maximizing immediate output. However, for long-duration performance, this distance did not prove most effective, suggesting involved factors at play over extended periods. The experiment revealed a significant increase in temperature when sunlight covered the entire active region, resulting in a decline in output performance. This also revealed that the direction of sunlight was shifting, emphasising the possible synergies between Fresnel lenses and solar trackers. In spite of a little lower voltage, Case 1 in terms of current and power output, the system's ability to capture energy is greatly increased by the focused sunlight produced by the Fresnel lens. Thus, it is advised to employ a Fresnel lens with a concentrator at 0 cm onto the solar panel for the Concentrator Photovoltaic Thermoelectric Generator (CPV-TEG) system to function at its best. Analysing average metrics across four cases revealed that the Fresnel lens resulted in increased voltage and power outputs, with some variability in current flow. Finally, these findings highlight the complexities of optimising solar energy systems with Fresnel lenses, emphasising the importance of taking into account factors such as sunlight coverage, temperature dynamics, and potential synergies with complementary technologies such as solar trackers in order to achieve optimal and sustainable performance.

4. Conclusion

In a conclusion, this study provided a thorough investigation of the complex dynamics controlling a CPV-TEG system's performance. The primary goal of this research was to create an efficient CPV-TEG system that could collect energy from both sunshine and temperature differences. The integration of a Fresnel lens as a solar concentrator and six TEG modules allows for a comprehensive energy harvesting method through rigorous planning and implementation. The incorporation of IoT technologies into the CPV-TEG system was a noteworthy accomplishment. The project accomplished real-time monitoring capabilities by utilizing the Arduino IDE software and the ThingSpeak platform. This addition not only improved data precision, but also paved the way for future advances in smart and networked renewable energy systems. A thorough comparative analysis was performed, assessing the output of the CPV-TEG system under four separate circumstances. For each scenario, different Fresnel lens placements and durations were rigorously investigated. The goal of this study was to learn more about the subtle effects of Fresnel lens location on system performance and energy production.

This study endeavor into the dynamics of a CPV-TEG system yielded useful insights. A dynamic tracking system for real-time orientation modifications, assuring continuous exposure to sunshine, might be incorporated to improve system efficiency. Implementing an active cooling mechanism appears to be a promising method to combat temperature-induced voltage and power output reductions. Furthermore, possible enhancements like as grid integration and collaborative research initiatives open the door to broader applications and increased economic feasibility. These ideas, developed through a methodical and interdisciplinary approach, aim to accelerate the CPV-TEG system towards becoming a sophisticated, adaptive, and economically competitive renewable energy solution.

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