Design and Fabrication of Concentrated Photovoltaics

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Abstract

To mark the corresponding low Efficiency of Photovoltaic (PV) systems, a unique concentrator was developed to strengthen the intensity of solar irradiance falling on the surface of PV, therefore upgrading its power output. A best design for a Concentrated Photovoltaic (CPV) system was visualize and constructed, featuring a workable concentration mechanism that authorizes the adjustment or complete removal of the concentrator depend on operational requirements. Comprehensive experimental evaluations were performed on this system. Results presented that by using a low-level concentrator led to an increase of 39.85% under clear-sky environments, while its performance decreases under rainy or cloudy weather due to the dependency on direct sunlight. Important challenges just like optical misalignment, thermal buildup, and lowered performance under diffuse light were investigated, and practical techniques to reduce these problems were discussed. The results showed both the abilities and the limitations of low-concentration CPV systems in the region with variable irradiance, providing insights for future optimization through advanced thermal management, optical design, and adaptive tracking techniques.

Keywords: Concentrated Photovoltaics, Fresnel Lens, Efficiency, Design and Fabrication.

Introduction

In the modern era, a reliable and efficient energy supply is fundamental to both economic development and societal well-being. However, energy production is closely linked with environmental consequences. Amid growing concerns about global warming and climate change, it has become imperative to develop energy systems that not only fulfill rising global energy demands but also minimize or eliminate environmental harm (Olabi, 2016). Traditionally, fossil fuels have been the dominant source of energy worldwide. However, the rapid depletion of these resources, coupled with their significant environmental drawbacks particularly their role in greenhouse gas emissions and climate

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change has raised critical concerns about their long-term sustainability (Muneer et al., 2006). In response, the global energy landscape is undergoing a profound transformation, characterized by a shift toward cleaner, renewable sources of energy. Over the past fifteen years, renewable energy especially solar energy has witnessed rapid growth, driven by advances in technology, increased investment, and widespread adoption, particularly in developing countries (Sen & Ganguly, 2017).

One of the most promising renewable energy technologies is PV energy, which directly converts solar radiation into electrical energy using solar cells made of semiconductor materials. Each cell generates both current and voltage, but the output of a single cell is typically insufficient for practical applications. To overcome this limitation, multiple cells are connected in series and/or parallel to form solar panels, thereby producing voltage and current levels suitable for a wide range of uses. While the current output is primarily dependent on the intensity of incident sunlight and is difficult to regulate, voltage can be effectively controlled through cell configuration (Schropp & Zeman, 1998).To further enhance the performance of PV systems, CPV technology has emerged as a promising solution. CPV systems utilize optical elements such as lenses or mirrors to concentrate sunlight from a larger collection area onto a smaller PV surface. This concentration significantly increases the solar irradiance incident on the cells, thereby boosting their energy capture and overall efficiency (Boxwell, 2010). Even modest gains in solar cell efficiency, such as a 1% increase can have substantial economic implications, as they reduce the number of modules required to meet energy generation targets. Consequently, this leads to lower balance-of-system costs and decreases both maintenance and operational burdens (Wiemer et al., 2011). However, one of the critical limitations of CPV systems is thermal buildup caused by the concentrated solar radiation. The excessive heat, especially when optical devices like Fresnel lenses are used, can lead to performance degradation or even physical damage to the PV modules. Effective thermal management remains a significant challenge in enhancing the efficiency and durability of CPV systems (Chu & Meisen, 2011).

Among different renewable energy technologies, PV systems have proven to be one of the most feasible and capable solutions for conversion of solar radiation directly into electricity. PV cells, basically made from semiconductor materials like silicon, operate by absorbing photons and releasing electrons, thus producing electric current. Moreover, the voltage and current output from a single PV cell are least and inadequate for most practical applications. To meet real-world energy needs, individual cells are connected in series and/or parallel to form modules or arrays, thereby scaling up the system's voltage and current capacity (Hasan et al., 2023). While PV systems are relatively simple, modular, and environmentally friendly, their performance is strongly affected by climatic conditions, especially solar irradiance. The current output is difficult to control directly as it changes with sunlight intensity, whereas the voltage can be managed through suitable circuit configurations and load matching (Koohi-Kamali et al., 2014). In pursuing of greater efficiency and better land utilization, CPV technology has appear as an advanced solution to control some intrinsic limitations of traditional flat-plate PV systems. CPV systems engage optical concentrators such as Fresnel lenses, parabolic mirrors, or other refractive/reflective optics to concentrate on a large area of sunlight onto a small, high-efficiency solar cell surface. This approach allows a decrease in the quantity of PV material required, potentially decreasing system costs while increasing power density (Vodapally & Ali, 2022).

Various researches have shown that even a modest 1% improvement in solar cell efficiency can lead to remarkable economic benefits by decreasing the number of modules, land use, and supporting infrastructure need to meet a specific energy output (Choi et al., 2021). However, higher efficiencies in CPV systems translate to lower Levelized Cost of Electricity (LCOE), making them suitable for large-scale deployments in high DNI (Direct Normal Irradiance) countries (Abdelhady, 2025). Despite these advantages, CPV systems face various technical issues that limit their worldwide adoption. One of the initial issues is thermal buildup, a consequence of the concentrated solar flux incident on the surface of cell. When sunlight is concentrated using optical components like Fresnel lenses, the local temperature of the PV cells can increase quickly, guiding to decreased efficiency, faster degradation of cell materials, and potential structural damage ("High-Concentration Optics for Photovoltaic Applications," 2015).

Unlike flat-plate PV systems, CPV modules are more sensitive as compare to PV module to thermal variations due to their higher power density. Therefore, thermal management becomes a critical aspect of CPV system design, requiring either passive or active cooling policies to maintain operational stability and ensure long-term performance (Xie et al., 2025). However, the optical components used in CPV, such as lenses or mirrors, must maintain high transmittance or reflectance and avoid soiling or surface degradation, which can severely influence performance. Another critical requirement for efficient CPV working is accurate solar tracking. Unlike flat-plate systems that can allow a greater angle of light incidence, CPV systems need precise alignment with the sun to make certain that concentrated light is successfully focused onto the cell surface. Dual-axis solar tracking systems are usually employed for this purpose, but they increase complexity and cost of system, specifically for small-scale or domestic applications (Kazem et al., 2024). Moreover, CPV systems tend to perform poorly under diffuse light conditions, such as in cloudy or overcast weather, because they depend exclusively on direct sunlight. In such case, the optical concentrator may even decrease the net irradiance reaching the PV cell due to shadowing or light loss, making flat-plate PV modules more effective under various weather conditions (Amanlou et al., 2016).

In the current research, Fresnel lenses were chosen as the optical concentrators due to their distinctive applications over alternatives such as parabolic mirrors. Fresnel lenses are inexpensive, lightweight, and relatively easy to develop, making them suitable for low-cost CPV system development. Their flat and compact geometry decreases bulk while still authorizing high concentration ratios, so that reducing the quantity of PV material needed. Moreover, they are simple to integrate into small-scale prototypes due to their easy mounting and alignment, which is especially best in experimental work performed under resource constraints. These attributes make Fresnel lenses a practical choice for appreciating CPV viability in local climatic regions such as those of Peshawar. The experimental results investigate that while low-concentration CPV systems can strengthen power output obtaining up to 39.85% improvement under clear sky conditions their performance is highly inconsistent under changing weather due to their dependency on direct sunlight and the shadowing influence of the Fresnel lens in diffuse light.

A remarkable research gap exists in the optimization of CPV systems for real-world conditions. Basic limitations identified include unsuitable thermal management under high irradiance, suboptimal lens-to-panel area ratios investigating in partial concentration, lack of dual-axis sun tracking which decreases system efficiency beyond short time windows, and significant power losses caused by optical reflections when glass layers are used around the lens. Thermal management is an important design issue for CPV systems, as overheating can decrease performance and accelerate aging of the material. Different techniques have been investigating in prior studies to address this problem, including passive cooling methods just as fins, heat sinks, and phase-change materials, and active cooling approaches using forced air circulation or liquid cooling systems. While this research work did not implement a cooling mechanism, it appreciates the significance of such solutions and endorse their integration in future CPV designs to guarantee stable working under high irradiance environment. Moreover, soiling of the Fresnel lens surfaces shows maintenance issues that further decrease performance, yet no effective cleaning or protective policies were implemented. The absence of adaptive mechanisms to cope with environmental variability, combined with the lack of economic and long-term performance analysis, investigates the requirement for future research study focused on developing integrated, weather-adaptive, and thermally regulated CPV systems with improved optical matching, automated tracking, and low-maintenance design specifically suitable for climates like Peshawar’s with varying solar conditions.

Despite comprehensive worldwide research on CPV systems, a remarkable gap exists in investigating their performance under variable real-world weather conditions, especially in areas like Peshawar that undergoes a mix of clear and cloudy skies. Most previous research work have either concentrated on large-scale, high-cost CPV systems with modern tracking and cooling mechanisms or performed experiments solely under high direct normal irradiance conditions, which do not show the issues of developing areas. The novelty of the current research lies in development and experimentally testing a low-cost, small-scale CPV prototype with the help of Fresnel lenses and comparing its performance with flat-plate PV modules under same outdoor conditions. The basic aim of this work is to identify the advantages and limitations of CPV systems in such environments, showing basic issues such as thermal buildup, shadowing under diffuse light, and lens-to-panel optical mismatch, thereby facilitating insights for future optimization and adaptation of CPV technology for regional applications.

Recent research has focused both the strong solar resource in Pakistan and the emerging interest in concentrated-solar technologies for high-DNI areas. National judgement and techno-economic work represent Pakistan’s high solar ability and distinguish concentrated solar approaches as attractive choice for utility-scale and hybrid systems in the region of high-irradiance (Muhammadi et al., 2024). At the same time, various latest experimental studies have basically investigated Fresnel-lens CPV configurations and practical cooling techniques, highlighting that low-cost Fresnel lenses can be important concentrators for small-scale CPV prototypes but that thermal management (passive and active) is critical to avoid interpretation loss at high flux densities (Singhy et al., 2022). Comprehensive recent work of CPV performance and thermal features further enhance that while CPV can provide efficiency and material-cost application in high-DNI system, opportunities such as lens-to-cell optical mismatch, soiling, lens-to-cell optical mismatch, and the requirement for integrated cooling and tracking systems remain important research priorities (Zou et al., 2024).

Methodology

Design of the Concentrated Photovoltaic Prototype

The prototype of the CPV system was designed using Creo software. Four systems were mounted on a single base, as illustrated in Figure 1. These included two CPV systems and two conventional PV modules. The first CPV setup incorporated a 5-watt PV module, which was compared with a 5-watt flat-plate PV module, as shown in Figure 2. The second CPV system used a 1.1-watt PV module, paired for comparison with a flat-plate PV module of the same rating. In both configurations of CPV, the modules of PV were installed in a vertical orientation. The CPV prototype was installed in vertical orientation in order to preserve focal alignment of lens–cell, while the flat-plate PV was placed in horizontal direction in order to show typical rooftop mounting. Although orientation may change irradiance, both modules were tested in the same environment, and findings are explained comparatively. The Fresnel lens whose were mounted in a frame, was positioned above each module with the help of steel rods. These rods were used for adjustment of the lens-to-module distance, for control over the concentration ratio as required.

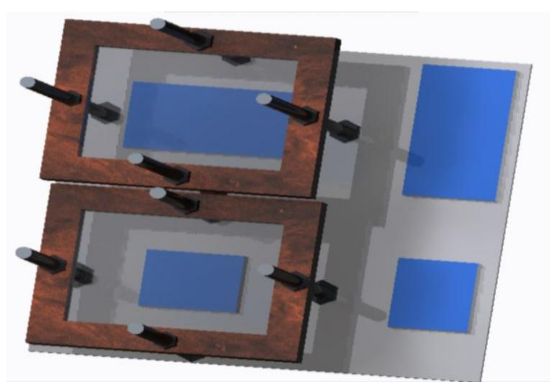

Figure 1: Integration of Fresnel lens Above PV Cells in a CPV Setup.

The distance between the Fresnel lens and the PV module was fixed experimentally to obtained a best focal spot on the cell: 4 inches were used for the 5 W module, where the spot only partially covered the surface, and 6 inches were used for the 1.1 W module, where the spot nearly comparable with the cell size. The effective concentration level was evaluated by comparing the irradiance in the concentrated spot with the ambient solar irradiance, guaranteeing that performance comparisons were depend on measured rather than purely theoretical values. Nuts were used for securing both the Fresnel lens and the overall structure in place. Similarly, the flat-plate PV modules were placed horizontally to reduce the footprint of the system and decease the use of additional materials.

Orientation Assumptions

- The CPV modules were mounted vertically to maintain lens–cell focal alignment, which is critical for concentration accuracy.
- The flat-plate PV modules were mounted horizontally to replicate typical rooftop installation practices.

Fabrication

The main objective of this research is the fabrication of a CPV system and the comparison of its performance with conventional flat-plate PV modules. The system is designed to include two flat-plate PV modules and two CPV units, all mounted on a single base. This configuration guarantee that all modules experience same solar angles and environmental conditions during testing. The fabrication process of the system is performed in multiple stages, which are discussed step-by-step as follows:

Frame for Fresnel Lens

For the two Fresnel lenses the frames were developed using PVC plastic, with each frame measuring 13 inches by 10 inches and having a width of 1.5 inches, as shown in Figure 2. The frames were designed just like to traditional photo frames but without a solid back panel, with the the center section open. To support mounting, 10.5 mm diameter holes were drilled at the center of each of the four sides of both frames, allowing 10 mm steel rods to pass through, as shown in Figure 2. The Fresnel lenses were inserted from the rear side of the frames, and their edges were secured using transparent adhesive tape along the sides and corners. Additionally, 1-inch nails with a thickness of 2 mm were gently hammered into the frame to further secure the lenses in place.

Bases for CPV the System

To construct the base of the system, aluminum sheets were used with two sizes: sheets 4 inches wide and angled at 0.5 inches, and additional sheets 6 inches wide. The base was designed as a square, measuring 21 inches by 21 inches. This size was selected to accommodate two vertically aligned Fresnel lenses; each housed in a PVC frame measuring 13 inches by 10 inches. When placed vertically, the combined width of the two lenses is 20 inches, leaving a 1-inch gap between them. The flat-plate PV module rated at 5 watts, with dimensions of 8.26 inches by 4.13 inches, was mounted horizontally. Its placement alongside the

CPV modules brought the system's total width to approximately 17.13 inches.

Figure 2: Integration Frame used to hold the Fresnel lens.

To avoid shadowing from the Fresnel lenses onto the flat PV modules, a 4-inch separation was maintained between the CPV and standard PV panels. The 4-inch-wide aluminum sheets were cut into five segments, each 21 inches in length. Four of these segments were riveted together to form the square outer frame of the base. A 6-inch-wide aluminum sheet was then fixed across the center to divide the base into two compartments for mounting the CPV units. The fifth 4-inch sheet was attached 5 inches from the bottom edge of the base, creating a 5-inch by 21-inch rectangular section to accommodate the standard PV module, as shown in Figure 3.

Figure 3: Base for the CPV system.

While rivets were used to fasten the aluminum structure, they were not suitable for attaching the PV modules themselves, since this design allows for the adjustment and replacement of modules and concentrators. Instead, liquid silicon adhesive was applied to secure the PV modules to the base. The adhesive was spread on both contact surfaces and left to cure, ensuring a firm but removable bond. The flat-plate PV modules were placed in the lower corners of the base, within pre-designated sections visible in Figure 3. The PV modules for the CPV setup were positioned vertically, 3.2 inches from the top and sides of the base. A 6.3-inch gap was maintained between the two CPV modules to accommodate the larger Fresnel lenses, ensuring they would not touch. Ultimately, a clearance of 0.2 inches was maintained between the two lenses. To align the Fresnel lens frames with the PV modules, holes were drilled on all four sides of each CPV module mounting location, directly below the corresponding holes in the lens frames. This alignment allowed the steel rods to pass cleanly through both the base and the frames. The final arrangement of the drilled holes is shown in Figure 3. After drilling, sandpaper was used to smooth out the aluminum surface and remove any sharp or uneven edges from the base.

Rods and Painting

Following the drilling of holes in the base, steel rods with a diameter of 10 mm and a length of 14 inches each threaded on both ends were inserted through the aligned holes. On both sides of each rod nuts were fastened to securely fix them to the aluminum base. The rods were placed so that almost one inch extended below the base, allowing them to work as support legs to elevate and stabilize the structure. Once all rods were positioned in place, the whole base was coated with a bright chrome spray paint to strengthen its visual appearance and provide a clean, finished look. The completed base structure is presented in Figure 4.

Figure 4: Base of the system after painting.

Developing of CPV System

The final step of the fabrication process included assembling the CPV. With the steel rods firmly fastened to the base, the Fresnel lens frames were precisely inserted from the top side of the rods. Each frame was then fixed in place with the help of nuts both above and below the frame, guaranteed a stable and adjustable mounting on the rods. This configuration authorized for best control of the lens fixed relative to the PV modules. The completed CPV system setup is shown in Figure 5.

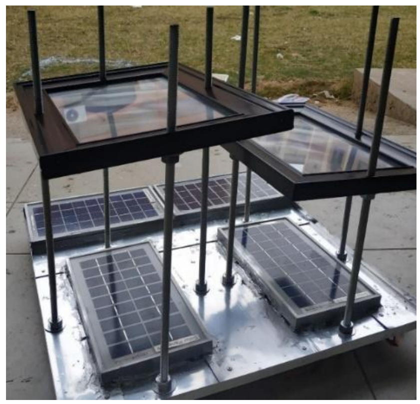

Figure 5: Fresnel lens placed over PV module.

Validation of Results

The theoretical vs Experimental Concentration

Theoretical concentration ratios (based on lens-to-cell geometry) were compared with measured focal irradiance to confirm consistency.

Comparison with STC Values

Output power of flat-plate PV modules was compared against manufacturer datasheet values at Standard Test Conditions (STC: 1000 W/m², 25 °C) to verify measurement accuracy.

Repeatability

Tests were repeated on multiple days, and performance trends were consistent within ±7%, confirming reliability.

Results and Discussion

Outdoor experimental testing and performance comparison were performed between the CPV systems (5-watt and 1.1-watt) and their respective conventional flat-plate PV modules (5-watt and 1.1-watt). These experiments were conducted in different weather conditions on the rooftop of USPCASE, UET Peshawar. Important parameters measured during the testing included DC current, solar irradiance, DC voltage, output power, the power ratio of the CPV system to the corresponding flat-plate PV module, and the percentage increase in power output obtained by the CPV systems. These metrics were evaluated and analyzed for both the 5-watt and 1.1-watt setups to assess the performance enhancement provided by concentration.

PV Module of 5watt Data

This work presents the experimental results obtained from testing a conventional 5-watt PV module and a 5-watt CPV system under various weather conditions on different days. In the CPV configuration, the Fresnel lens was positioned at a minimum feasible distance of 4 inches above the PV module. This close placement was intended to maximize the irradiance coverage on the PV surface. However, due to the low size ratio between the Fresnel lens and the PV module, the concentrated solar irradiance did not fully cover the entire surface of the PV module, resulting in a smaller spot size.

During testing, a digital multi-meter was used to measure current, open-circuit voltage, and temperature. Direct solar irradiance was measured using a pyranometer connected to a data logger. Electrical power output was calculated by multiplying the measured current and voltage, as represented in Equation 1. The power ratio was determined by dividing the CPV system's power output by that of the flat-plate PV module (Equation 2). The percentage increase in power output was calculated by multiplying the CPV system's power by 100, dividing by the power of the simple PV module, and subtracting 100, as described in Equation 3. The collected experimental data is summarized in Table 1.

$$P = I_{sh} \text{x}\, V_{op} \quad (1)$$

$$Power\ Ratio = \frac{Power\ of\ CPV\ System}{Power\ of\ Simple\ PV\ Module} \quad (2)$$

$$Percent\ Power\ Increase = \{(P_{cpv}\ \text{x}\ 100)/P_{pv}\} - 100 \quad (3)$$

Performance Comparison of CPV and Flat-Plate PV Systems Under Varying Weather Conditions

On clear sunny days, the incident solar irradiance on the CPV system increased significantly due to the focusing effect of the Fresnel lens, which performs best under direct sunlight. In contrast, during cloudy and rainy weather, the irradiance on the CPV system decreased considerably. This is because the Fresnel lens, which relies on direct sunlight for concentration, casts a shadow under diffuse light conditions, reducing the irradiance reaching the PV module. Conversely, flat-plate PV modules perform better under such diffuse conditions, as they are able to capture scattered light more effectively.

The electrical current in both the CPV and flat-plate PV systems increased proportionally with increasing irradiance. On sunny days, the

CPV system generated a higher current than the flat-plate PV module because of the intensified light concentration. Current readings were taken using a digital multimeter while a load was applied. The maximum current recorded was 0.064 A at an irradiance level of 1028 W/m² on June 20th for the CPV system. Interestingly, the same current value (0.064 A) was also recorded for the flat-plate PV module at a slightly lower irradiance of 956 W/m² on the same day. This minimal difference is attributed to the Fresnel lens's limited spot size, which did not fully cover the PV module in the CPV system.

Table 1: Physical Output data of 5watt simple PV panel with CPV system with 5watt PV panel *FP is for Flat Plate.

Date and Time	*Module Type*	*Irradiation W/m²*	*Current (A)*	*Volt (V)*	*Temp (°C)*	*Power (Watt)*	*Power Ratio= (Pcpv/Ppv)*	*Percent Power Increase*
2-May-24	FP PV	869	0.061	9.52	45	0.58072	1.0105042	1.05042
	CPV	955	0.061	9.62	55	0.58682		
3-May-24	FP PV	868	0.061	9.51	45	0.58011	1.01051525	1.051525
	CPV	953	0.061	9.61	55	0.58621		
6-May-24	FP PV	826	0.059	9.33	41	0.55047	1.01178992	1.178992
	CPV	912	0.059	9.44	47	0.55696		
7-May-24	FP PV	949	0.063	9.81	54	0.61803	1.00203874	0.203874
	CPV	1019	0.063	9.83	60	0.61929		
15-May-24	FP PV	962	0.063	9.83	56	0.61929	1.00101729	0.101729
	CPV	1036	0.063	9.84	62	0.61992		
20-May-24	FP PV	181	0.017	3.09	28	0.05253	0.60727204	-39.2728
	CPV	90	0.011	2.9	26	0.0319		
12-Jun-24	FP PV	320	0.03	5.96	26	0.1788	0.72192394	-27.8076
	CPV	282	0.028	4.61	24	0.12908		
13-Jun-24	FP PV	530	0.042	7.15	30	0.3003	0.95844156	-4.15584
	CPV	496	0.041	7.02	29	0.28782		
14-Jun-24	FP PV	355	0.03	5.97	27	0.1791	0.93266332	-6.73367
	CPV	305	0.029	5.76	25	0.16704		
15-Jun-24	FP PV	879	0.061	9.52	48	0.58072	1.01155462	1.155462
	CPV	963	0.061	9.63	56	0.58743		
16-Jun-24	FP PV	874	0.061	9.51	47	0.58011	1.0126183	1.26183
	CPV	959	0.061	9.63	56	0.58743		
17-Jun-24	FP PV	899	0.062	9.63	49	0.59706	1.0145379	1.45379
	CPV	991	0.062	9.77	58	0.60574		
18-Jun-24	FP PV	917	0.063	9.71	52	0.61173	1.01029866	1.029866
	CPV	1005	0.063	9.81	58	0.61803		
19-Jun-24	FP PV	925	0.063	9.74	53	0.61362	1.00718686	0.718686
	CPV	1012	0.063	9.81	59	0.61803		
20-Jun-24	FP PV	953	0.064	9.79	55	0.62656	1.00510725	0.510725
	CPV	1028	0.064	9.84	61	0.62976		
21-Jun-24	FP PV	845	0.06	9.47	43	0.5682	1.01055966	1.055966
	CPV	933	0.06	9.57	51	0.5742		

The lowest current recorded for the CPV system was 0.011 A at 90 W/m² irradiance on May 20th, while the flat-plate PV module registered a higher current of 0.017 A at 181 W/m². This outcome further emphasizes the CPV system's reduced performance under cloudy conditions due to the shadowing effect of the Fresnel lens, which limits both direct and diffuse light input.

Voltage readings were also obtained using a multimeter, with measurements taken under open-circuit conditions (i.e., no load). The highest voltage measured in the CPV system was 9.84 V at irradiance levels of 1036 W/m² on May 15th and 1028 W/m² on June 20th. For the flat-plate PV module, voltages of 9.83 V and 9.79 V were recorded on the same respective days under irradiance levels of 962 W/m² and 953 W/m². The slight voltage increase in the CPV system can again be explained by the limited concentration area of the Fresnel lens.

The lowest voltage recorded was 2.9 V at 90 W/m² irradiance on May 20th for the CPV system, compared to 3.09 V at 181 W/m² for the flat-plate PV module. The reduced voltage in the CPV setup is mainly due to the Fresnel lens blocking diffuse irradiance during overcast conditions.

Temperature variations were also monitored and showed a direct correlation with irradiance levels. The highest temperature recorded was 62°C in the CPV system at 1036 W/m² irradiance on a sunny day, while the lowest temperature was 24°C at 282 W/m² on a cloudy day. Despite this increase, the temperature remained within acceptable limits, and no additional cooling was deemed necessary for the PV modules.

The highest current and voltage output for the CPV system was recorded on June 20, 2024, when the solar irradiance reached 1028 W/m². On this day, the CPV system generated a power output of 0.62976 watts. In comparison, the simple PV module, exposed to a slightly lower irradiance of 956 W/m² on the same day, produced 0.62656 watts. The marginal increase in the CPV system's performance can be attributed to the Fresnel lens's ability to concentrate sunlight, although the benefit was limited due to the smaller spot size of the lens relative to the size of the PV module, resulting in only partial coverage.

On May 20, 2024, the lowest current and voltage values were observed for the CPV system, corresponding to a low solar irradiance of 90 W/m² under cloudy conditions. The CPV system produced a power output of 0.0319 watts on this day. In contrast, the flat PV module, receiving a higher irradiance of 181 W/m², delivered a power output of 0.05253 watts. The reduced output from the CPV system in this case is linked to the shadowing effect caused by the Fresnel lens, which diminished the amount of diffuse sunlight reaching the PV surface during overcast weather.

The performance comparison between the CPV system and the flat PV module was further evaluated by calculating the power ratio, which is the quotient of the power output of the CPV system and the simple PV module. The highest ratio was obtained on June 20, 2024, with a value of about 1.005, showing a little performance gain of the CPV system over the flat panel. The lowest power ratio was observed on May 20, 2024, about 0.607, which shows the lower efficiency of the CPV setup during cloudy environment. An assessment of the percentage difference in power output showed that the CPV system recorded its highest performance increase on June 17, 2024, with a gain of around 1.45 percent compared to the simple PV module under an irradiance level of 899 W/m². Conversely, a significant drop in performance, approximately negative 39.27 percent, was recorded on May 20, 2024, under low irradiance conditions. This decline is largely due to the poor performance of the Fresnel lens system in diffuse lighting, where it focusing ability becomes ineffective and actually reduces the total energy captured by the PV surface.

PV Module of 1.1-watt Data

Experimental data for both a 1.1-watt rated simple PV module and a 1.1-watt rated CPV system were collected over multiple days under varying weather conditions. The Fresnel lens was fixed at a height of 6 inches above the PV module, as this distance provided the best spot size to usefully cover the total surface of the 1.1-watt module. This configuration was chosen to ensure maximum performance while preventing any potential hazard to the PV module from concentrated sunlight. Current, voltage, and temperature were measured with the help of multi-meter, whereas direct solar irradiance was observed by using of a pyranometer and data logger. Power output was measured as the product of the measured current and voltage. The power ratio, used to find the relative performance of the CPV system compared to the simple PV module, was calculate, the CPV system’s power output divided by that of the flat PV module. The percentage increase in power was found by comparing the CPV system’s output to the flat panel with the help of a standard formula. The detailed experimental results for this setup are presented in Table 2.

The Irradiance levels were observed to increase on clear, sunny days when direct sunlight was abundant and effectively concentrated onto the CPV system through the Fresnel lens. Given the lens’s efficiency under direct sunlight, irradiance on the CPV system decreased during overcast and rainy conditions, where diffuse sunlight dominates. In contrast, the standard PV panel performed relatively better on cloudy days due to its capacity to utilize diffuse light, while the CPV system experienced a reduction in performance due to the Fresnel lens casting shadows that further diminished the available irradiance.

Table 2: Output parameters of 1.1watt simple PV module and CPV system with 1.1watt PV module *FP is for Flat Plate.

Date and Time	*Module Type*	*Irradiation W/m²*	*Current (A)*	*Volt (V)*	*Temp (⁰C)*	*Power (Watt)*	*Power Ratio (Pcpv/Ppv)*	*Percent Power Increase*
16-July-24	FP PV	844	0.03	6.55	36	0.1965	1.31307888	31.30789
	CPV	1179	0.038	6.79	67	0.25802		
17-July-24	FP PV	863	0.031	6.59	38	0.20429	1.26858877	26.85888
	CPV	1191	0.038	6.82	68	0.25916		
18-July-24	FP PV	198	0.016	3.71	27	0.04976	0.65554662	-34.4453
	CPV	112	0.014	2.33	27	0.03262		
19-July-24	FP PV	871	0.03	6.53	39	0.1959	1.32679939	32.67994
	CPV	1201	0.038	6.84	66	0.25992		
20-July-24	FP PV	726	0.024	6.44	31	0.15456	1.39848602	39.8486
	CPV	960	0.033	6.55	43	0.21615		
21-July-24	FP PV	755	0.029	6.42	35	0.18618	1.23509507	23.50951
	CPV	972	0.035	6.57	43	0.22995		
22-July-24	FP PV	652	0.025	6.36	30	0.159	1.27119497	27.1195
	CPV	887	0.031	6.52	38	0.20212		
23-July-24	FP PV	742	0.028	6.4	31	0.1792	1.24274554	24.27455
	CPV	960	0.034	6.55	42	0.2227		
24-July-24	FP PV	866	0.031	6.51	40	0.20181	1.28606115	28.60611
	CPV	1197	0.038	6.83	66	0.25954		
25-July-24	FP PV	944	0.034	6.58	41	0.22372	1.19412659	19.41266
	CPV	1389	0.039	6.85	77	0.26715		
26-July-24	FP PV	1032	0.036	6.66	45	0.23976	0.85464631	-14.5354
	CPV	1451	0.031	6.61	85	0.20491		
27-July-24	FP PV	995	0.035	6.55	40	0.22925	0.92545256	-7.45474
	CPV	1403	0.032	6.63	81	0.21216		
28-July-24	FP PV	836	0.03	6.47	38	0.1941	1.28670788	28.67079
	CPV	1159	0.037	6.75	61	0.24975		
29-July-24	FP PV	945	0.034	6.53	39	0.22202	1.08143411	8.143411
	CPV	1396	0.035	6.86	78	0.2401		
30-July-24	FP PV	237	0.019	4.15	29	0.07885	0.915409	-8.4591
	CPV	195	0.018	4.01	29	0.07218		
31-July-24	FP PV	801	0.03	6.45	39	0.1935	1.25209302	25.2093
	CPV	1125	0.036	6.73	63	0.24228		
01-Aug-24	FP PV	855	0.031	6.49	41	0.20119	1.245042	24.5042
	CPV	1169	0.037	6.77	68	0.25049		
02-Aug-24	FP PV	841	0.031	6.47	40	0.20057	1.24520118	24.52012
	CPV	1160	0.037	6.75	67	0.24975		
03-Aug-24	FP PV	167	0.016	3.01	26	0.04816	0.67151163	32.8488
	CPV	101	0.014	2.31	26	0.03234		
04-Aug-24	FP PV	567	0.022	6.29	29	0.13838	1.09784651	9.784651
	CPV	625	0.024	6.33	30	0.15192		
05-Aug-24	FP PV	809	0.03	6.46	39	0.1938	1.25201238	25.20124
	CPV	1131	0.036	6.74	65	0.24264		
06-Aug-24	FP PV	813	0.03	6.47	40	0.1941	1.25007728	25.00773
	CPV	1138	0.036	6.74	66	0.24264		

Current output in both systems rose in response to increasing irradiance. On bright, sunny days, the CPV system generated more current than the simple PV module, attributed to the higher intensity of focused sunlight. Current readings were taken using a multi-meter while a load was applied to each system. The maximum current of 0.039 A was recorded on July 20, 2024, under 1389 W/m² of irradiance using the CPV setup. On the same day, the simple PV module registered a current of 0.034 A under 944 W/m². On rainy days, such as August 3 and July 18, 2024, the CPV system recorded its lowest current values of 0.014 A, whereas the simple PV panel measured slightly higher values of 0.016 A under irradiance levels of 167 W/m² and 198 W/m² respectively. This decline in CPV current is primarily due to both the reduced solar irradiance and the shadowing effect of the Fresnel lens, which limits diffuse light exposure.

Voltage measurements, taken with no load applied, revealed that the CPV system achieved its peak voltage of 6.85 V on July 25, 2024, at 1389 W/m². In comparison, the simple PV module recorded 6.58 V under 944 W/m² on the same day. The lowest CPV voltage was noted on August 3, 2024, at 2.31 V with irradiance of 101 W/m², while the simple PV module yielded 3.01 V under 167 W/m². The Fresnel lens again contributed to voltage reduction in diffuse-light conditions by casting shadows and limiting irradiance.

Temperature trends aligned closely with irradiance levels. The highest temperature observed was 85°C, corresponding to an irradiance of 1451 W/m² on a clear day, while the lowest temperature recorded was 26°C during a period of reduced solar input (101 W/m²). Although elevated temperatures were recorded, especially at peak irradiance levels, the average solar irradiance in Peshawar generally remained within a range where active cooling of the CPV system was unnecessary.

The highest power output from the CPV system was recorded on July 25, 2024, reaching 0.26715 W under 1389 W/m², whereas the simple PV module produced 0.22372 W under 944 W/m² on the same day. Conversely, the lowest power output from the CPV system was measured on August 3, 2024, at 0.03234 W under 101 W/m², compared to 0.05904 W from the simple PV panel under 167 W/m². These results again highlight the CPV system's limitations under cloudy conditions due to the Fresnel lens's interference with diffuse irradiance.

Power ratio analysis revealed that the highest value occurred on July 20, 2024, with a CPV power output of 0.21615 W compared to 0.15456 W from the simple PV module, resulting in a ratio of 1.39849. The lowest ratio was documented on July 10, 2024, where the CPV system generated 0.03262 W while the simple PV module produced 0.04976 W, yielding a ratio of 0.65555.

The percentage increase in power for the CPV system relative to the simple PV module was calculated accordingly. The greatest observed improvement was 39.85% on July 12, 2024, under 726 W/m² irradiance. However, on rainy days such as May 10, 2024, the CPV system experienced a reduction in output, with a negative power difference of 34.45% due to low irradiance and minimal contribution from diffuse light.

Discussion

The experimental results of the current research work are largely consistent with results from previous research study on low-concentration PV systems. This research demonstrated that CPV systems using Fresnel lenses can strengthen electrical output by up to 39.85% under clear sky conditions due to effective light concentration, matching with results investigated by ("Inspira's CPV Sun Tracking," n.d.) and (Baig et al., 2012), who obtained similar gains under high direct normal irradiance. Moreover, comparable to results from (Shanks et al., 2016), the performance of the CPV system in this research remarkably decreased during cloudy or diffuse light conditions, initially due to shadowing and limited diffuse light capture by the Fresnel lens a problem not encountered in conventional flat-plate PV modules. In terms of thermal impact, the current research recorded module temperatures as high as 85°C under high irradiance, which aligns with prior observations by (Sharaf et al., 2022), who presented that overheating decreases efficiency and can guided to material degradation. Unlike previous studies that proposed and tested passive or active cooling techniques (Xiao et al., 2018), the current research did not implement a cooling system, though it recognized the need for one under high irradiance conditions.

Another distinction lies in the system configuration. Many earlier CPV researches incorporated dual-axis tracking to maintain solar alignment and improve energy yield throughout the day (Angulo-Calderón et al., 2022). In contrast, the current study used a fixed system, resulting in suboptimal performance beyond peak sun hours due to lens misalignment and additional shadowing emphasizing the advantages of sun tracking in CPV systems. Moreover, the relatively small lens-to-panel area ratio in this research limited the focal spot coverage, decreasing the potential benefits of concentration. This contrasts with optimized CPV designs in previous work (Renno & Perone, 2021), where a better optical match guided to more consistent performance gains.

Additionally, the problem of soiling and maintenance difficulty of the Fresnel lens surface, as achieved in current study, supports the results of (Kolamroudi & Kordani, 2024), who investigate significant performance loss due to dust accumulation. Earlier efforts that presented self-cleaning coatings and cleaning mechanisms. The current research concentrated basically on performance comparison, without addressing long-term cost-effectiveness or durability presenting an avenue for future research. In short, the current results affirm established CPV behavior patterns under changing solar conditions, while underscoring the requirement for integrated tracking, cooling, cleaning mechanisms, and system optimization to strengthen CPV viability in real-world applications.

Under clear-sky environment, the CPV module developed a clearly greater short-term power output than the flat-plate PV because of the strong concentrating effect of the Fresnel lens. Although, during cloudy duration its performance dropped quickly, as Fresnel optics are not working properly at focused diffuse radiation, representing an important limitation of CPV in different environments. Moreover, a slow decrease in CPV output during more working was noticed, which can be assigned to thermal buildup at the focal spot, increasing cell temperature and decreasing efficiency, a problem was reported in earlier CPV research. The key performance difference between the two tested modules also shows lens-to-cell matching: the 1.1 W module profited more because the focused spot size nearly matched its active cell area, while the 5 W module tolerated from partial coverage and rough illumination. In general, these results are compatible with latest reports on Fresnel-lens CPV prototypes in high-DNI regions, which also noticed improved maximum efficiency but strong dependence on matching, thermal management, and sky conditions (Younes, 2023).

The current prototype showed a mounting of fixed Fresnel lens, which confined suitable concentration to periods of high solar altitude. While this route simplified construction and reduced costs, it restricted energy capture outside peak hours. The addition of single- or dual-axis tracking could considerably enhance performance by maintaining focal alignment throughout the day, but with increased complexity of system and cost.

Limitations

The Fresnel lenses were temporarily adjusted in their PVC frames with the help of transparent adhesive tape and small nails. While no cracking was noted during experiment, this low-cost mounting may develop minute misalignment, edge shading, or that can generate small optical losses. These effects were neglected in the current research and are therefore showed as a limitation. A limitation of the current research is the absence of long-term testing. In real outdoor working, soiling and dust deposition can decrease transmission of light through Fresnel lenses, while long term UV exposure may cause yellowing or surface wear that destroyed efficiency of focusing. These factors could guide to gradual performance decline and higher maintenance requirements, and therefore should be investigated in future studies to better assess system reliability.

Conclusion

A dual setup was implemented comprising two CPV systems and two flat-plate PV modules, rated at 5 watts and 1.1 watts respectively. The CPV systems incorporated Fresnel lenses mounted at heights of 4 inches (for the 5-watt system) and 6 inches (for the 1.1-watt system). Performance data were recorded across various days during May, June, and July 2024 on the rooftop of the USPCAS-E UET Peshawar facility in Pakistan. Based on the experimental outcomes, the following conclusions were drawn:

(1) Low-concentration CPV systems demonstrated the potential to enhance power output significantly, with observed increases reaching up to 39.85% compared to standard PV modules.

(2) On overcast and rainy days, where direct irradiance is limited and diffuse light dominates, the performance of CPV systems declines. However, in such conditions, removing the Fresnel lenses—an easily manageable adjustment—can help mitigate this issue and improve efficiency.

(3) Under high solar irradiance conditions (above 1000 W/m²), the CPV system can reach temperatures as high as 85°C. In such cases, implementing a cooling mechanism is essential. Without proper cooling, not only is the performance of the CPV system compromised, but there is also a risk of long-term degradation of the PV modules.

(4) The CPV system requires dual-axis sun tracking to maintain optimal alignment with the sun throughout the day. Without this, sunlight no longer focuses accurately on the PV module after approximately one hour, and output performance is reduced due to misalignment and additional shadowing from support structures and the Fresnel lens itself.

(5) Placing glass either above or below the Fresnel lens was found to reduce solar irradiance due to reflection and absorption losses, leading to lower system performance.

(6) A small ratio between the Fresnel lens and the PV panel area results in a limited focal spot, which in turn restricts the amount of light reaching the module. Similarly, insufficient height of the lens from the panel reduces the concentration effect, limiting any performance gains.

(7) Both CPV and flat-plate PV modules suffer from shadowing effects, which significantly impact their electrical output by blocking sunlight from reaching the active surface.

(8) The soiling effect is particularly problematic for the Fresnel lens, as its rough side makes cleaning difficult. Accumulated dust and dirt not only degrade optical performance but also lead to noticeable drops in electrical output.

Technical Terms

Concentrated Photovoltaic) (A solar technology that utilizes optical elements (e.g., mirrors or lenses) to focus sunlight onto a smaller, high-efficient PV cell); Direct Normal Irradiance (The amount of solar radiation obtained per unit area by a surface perpendicular to the rays of the sun); Fresnel Lens (A lightweight optical lens with focus grooves designed to concentrate sunlight, used in CPV systems); Thermal Management (The set of strategies used to control and disperse heat produced in solar cells to prevent loss of efficiency under focused sunlight); Optical Alignment (The accurate adjustment of lenses or mirrors with respect to PV cells to ensure that focused sunlight is precisely concentrated on the active cell area).

Author Contribution

Nadeem Ur Rehman (Writing of the original Draft); Muhammad Yousaf (experimentation); Muhammad Arif Khattak (review, editing, project administration); Abid Hussain (methodology, design); Taha Ghazal Baloch (fabrication, validation)

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