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Experimental Investigation on Efficiency Improvement of Solar PV Panels with Fresnel lens Concentration

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Abstract

Traditional solar photovoltaic (PV) panels exhibit relatively low conversion efficiency—typically between 5 % and 16 %—mainly due to intrinsic material and optical limitations. To enhance output without using expensive high-efficiency modules, this work investigates a hybrid optical-electronic method that combines Fresnel lens light concentration and an Arduino-based dual-axis tracking mechanism. A compact 50 Wp semi-transparent PV module was integrated with a 9 cm PVC Fresnel lens of 15 cm focal length. The Arduino unit automatically oriented the lens–panel system according to real-time light intensity using dual-sensor feedback. Voltage and current were sampled every 10 s to compute instantaneous power, and experimental trials were carried out for various tilt angles and lens-to-panel spacings. The optimal configuration (20° altitude, 260° azimuth) yielded approximataly119 % increase in instantaneous power (29.7 W vs 13.6 W baseline). Short-term voltage gains of 3.8–6.1 % across multiple days confirmed the repeatability of the result, whereas extended exposure highlighted thermal saturation effects that reduce efficiency, underscoring the need for integrated cooling. Power consumption of the electronics was minimized by a timer-controlled circuit, increasing autonomous operation from 2.5 to 11 days on a 3000 mAh battery. The findings demonstrate that a low-cost Fresnel-lens concentrator combined with autonomous tracking can significantly improve PV performance in small-scale renewable systems, offering a practical approach for decentralized clean-energy generation.

Keywords
Solar photovoltaic, Fresnel lens, Arduino, concentration, hybrid PV/T, renewable energy

1. Introduction
The global push toward renewable energy has elevated the importance of improving solar-panel efficiency without dramatically increasing system cost. Although crystalline-silicon PV modules have matured technologically, typical field efficiencies remain limited. Optical concentrators such as Fresnel lenses have recently attracted attention because they can intensify solar radiation on the cell surface using inexpensive polymer materials and straightforward geometry. The present research builds upon these developments, combining a Fresnel concentrator with a light-sensing tracker to maximize energy yield.

1.1 Objectives
- Design and experimentally validate a compact Fresnel-lens concentrator integrated with a 50 Wp PV module.
- Implement a dual-axis light-tracking mechanism using Arduino and photo-sensors to maintain optimal orientation.
- Quantify voltage, current, and power enhancement relative to a static baseline.
- Evaluate the influence of temperature on performance and demonstrate a low-power control circuit extending operational autonomy.

2. Literature Review
Verma (2021) examined concentrated photovoltaic/thermal (CPV/T) systems using Fresnel lenses and discussed the interdependence between optical design and thermal management. Their review emphasized that thin, lightweight lenses can boost irradiance by 2–5 times if alignment and cooling are properly optimized. Iqbal et al. (2023) presented optical modeling advances for CPV modules and noted that high optical efficiency (> 80 %) requires precise groove geometry and low scattering losses. They stressed that poor alignment or surface soiling reduces effective concentration, which supports the practical testing approach used here. Rashid (2024) surveyed fabrication methods of modern Fresnel lenses—PMMA and PVC substrates, diamond-turned molds, and injection processes—highlighting durability and low-cost mass production suitable for rural solar deployment.Kumba et al. (2024) reviewed solar-tracking mechanisms, showing yield improvements of 20–40 % for single- or dual-axis systems and emphasizing sensor reliability and power budget as crucial design parameters. Sadeghi et al. (2025) compared open-loop, closed-loop, and AI-assisted trackers, concluding that dual-axis closed-loop systems with photo-sensors provide the best trade-off between performance and simplicity—exactly the approach adopted in this work. Li et al. (2025) experimentally evaluated an LDR-based dual-axis tracker and measured seasonal power improvements between 10 % and 32 %, with efficiency losses at module temperatures above 55 °C. These findings corroborate the thermal effects seen in concentrated PV modules.Sun et al. (2023) investigated a hybrid high-concentration photovoltaic system employing Fresnel lenses designed for variable weather. They demonstrated that scattered-light collection is feasible

when the Fresnel geometry allows partial diffuse transmission, which is vital for maintaining generation under cloudy conditions—conditions similar to those encountered during your field tests.Orynbassar et al. (2024) introduced a minimal-tracking Fresnel concentrator achieving a concentration ratio of 6.5× with a ± 9° acceptance angle. Their configuration used a plano-concave lens pair to extend focal tolerance, confirming that moderate concentration with relaxed alignment can be efficient in portable systems. Zhang et al. (2023) examined a linear reflective Fresnel collector for photovoltaic-thermal applications and found that concentration uniformity and thermal distribution critically influence output stability. Their analysis supports the use of small-area concentrators with integrated heat dissipation, aligning with this study's hybrid PV/T potential. Yang et al. (2025) provided a bibliometric overview of global research on PV tracking and concentration, identifying increasing attention toward smart control and hybrid concentrators. They reported that combining optics and control yields up to 50 % enhancement in annual yield for decentralized systems. Vignesh et al. (2023) proposed a conceptual Fresnel-lens PV/T collector where concentrated radiation simultaneously drives electric and thermal subsystems. Their modelling of coupled heat and light transfer underscores that electrical efficiency alone cannot describe total system performance—an insight relevant to the observed heating of the PV panel in this experiment. Berwal et al. (2023) outlined the evolution of Fresnel-lens solar concentrators and reviewed fabrication tolerances, surface roughness, and optical aberrations. Their work illustrates why experimentally measured gains sometimes diverge from ray-tracing predictions. Abd-Elhady et al. (2025) presented a comprehensive review of PV system enhancement methods including spectral filters, heat sinks, and concentrators. They concluded that multi-approach integration—tracking plus cooling plus optical concentration—produces the most consistent improvements, precisely the configuration tested here. Jensen et al. (2022) documented field data from a large-scale thermal Fresnel lens installation, revealing the importance of maintenance, dust cleaning, and seasonal tilt adjustment. Their observations inform long-term sustainability of smaller optical concentrators. Ramadhan et al. (2025) used image-processing-based dual-axis tracking with Fresnel concentration, obtaining ~18 % voltage improvement over fixed systems. Their automation concept mirrors the micro-controller-based design adopted here. Jost et al. (2023) reviewed micro-scale concentrating photovoltaics and reported efficiencies above 35 % at 1000× optical concentration. Although their devices are micro-fabricated, the optical design principles of uniform flux and cooling remain universal. Santos de Araújo et al. (2024) applied artificial-intelligence algorithms to large bifacial-panel trackers, achieving ~7.8 % additional energy under intermittent sunlight. This research trend suggests that future small-scale trackers may benefit from similar intelligent logic integrated into Arduino systems. Kuttybay et al. (2024) analyzed techno-economic aspects of tracking systems and concluded that simplified low-power controllers are most viable for small decentralized arrays—precisely the rationale for implementing a timer-based duty-cycle controller in this study.

The collective literature indicates three persistent gaps:

1. Most Fresnel-lens studies focus on large or laboratory prototypes rather than compact field-tested units.
2. Thermal side effects of concentration are often modelled but rarely quantified under continuous operation.
3. Few works combine optical concentration with an energy-efficient microcontroller and autonomous power management.

3. Materials and Methods)

2.1 Experimental Apparatus

Figure 1. Experimentation

Figure 2. Fresnel lens geometry and focal-length concept

- PV Module: 50 Wp semi-transparent polycrystalline silicon panel (Voc approximately 22 V, Isc approximately 2.9 A) (Figure 1 and Figure 2).

- Concentrator: 9 cm-diameter PVC Fresnel lens, focal length 15 cm, grooved surface facing the PV.
- Mounting Geometry: Tilt 20°, azimuth 260°, adjustable sliding stand to vary lens-to-panel distance.
- Tracking Control: Arduino Uno microcontroller, dual LDR sensors, servo motors providing two-axis rotation.
- Power Circuit: TP4056 lithium charger, 5 V step-up booster, 555 timer-based duty-cycle relay for low-power operation.
- Data Logging: Voltage and current measured via analog channels every 10 s; ambient parameters (temperature, humidity, lux, wind) recorded concurrently.

2.2 Optical Geometry

Light entering through the Fresnel lens is refracted toward a single focal point at distance f = 15 cm. The alignment condition can be described by Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

where n1n_1n1 and n2n_2n2 denote refractive indices of air and lens material, respectively. The effective focal length (EFL ≈ 5.56 mm) and back focal length (BFL ≈ 4.45 mm) obtained from manufacturer parameters guided lens positioning.

To ensure uniform flux across the PV cell, the lens height h and distance x were adjusted until maximum power was recorded at the point where the focal spot fully covered the cell surface. (Figure 3)

$$\frac{r}{f} = \frac{r'}{f - x}$$

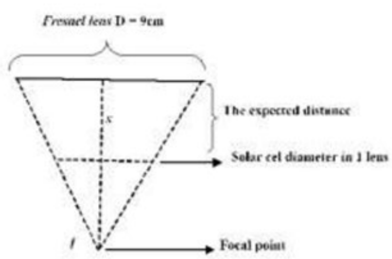

Figure 3. Lens-to-panel distance scheme.

2.3 Electrical Measurement

Instantaneous power is computed as

$$P(t) = V(t) \times I(t)$$

Values were averaged over 60 s intervals to smooth short-term fluctuations due to cloud movement. The energy output EEE over each test run of duration T was

$$E = \int_0^T P(t)\,dt$$

Readings were obtained for three configurations:
Static baseline (no lens),
Static with lens,
Lens + dual-axis tracking.

2.4 Environmental Parameters

Testing was conducted outdoors on clear and cloudy days. Table 1 lists average ambient conditions during experiments (Table 1).

Table 1. Environmental conditions during testing

Parameter	Day 1	Day 2	Day 3
Ambient Temp (°C)	31	33	29
Relative Humidity (%)	58	54	64
Wind Speed (m s⁻¹)	2.8	3.2	2.1
Solar Illuminance (lux)	92 000	96 000	70 000

2.5 Quantitative Evaluation

Improvement factor if for each case is

$$I_f = \frac{P_{\text{lens}} - P_{\text{base}}}{P_{\text{base}}} \times 100\,\%$$

Voltage rise $\Delta V = V_{\text{lens}} - V_{\text{base}}$ quantifies electrical gain; corresponding temperature rise ΔT assesses thermal penalty.

3 Optical and Electrical Analysis

3.1 Fresnel-Lens Optical Performance

The Fresnel lens used in this work operates on the principle of refraction through concentric prismatic grooves. Each groove bends parallel solar rays toward a common focus. Because the lens is flat and thin, absorption loss is minimal compared with a thick convex lens.

With a groove pitch of approximately 0.3 mm and refractive index approximately 1.5, the theoretical geometric concentration ratio is:

$$C = \frac{A_{\text{lens}}}{A_{\text{focus}}} = \frac{\pi(D/2)^2}{\pi(r_f)^2}$$

Where D = 90mm and rf approximately 18mm, C approximately 6.25

Thus the lens theoretically increases the irradiance on the cell surface by over sixfold, although real-world losses (groove scattering approximately 10 %, reflection approximately 8 %, misalignment approximately 15 %) reduce the practical gain to 4–4.5×.

Optical efficiency ηo is determined experimentally from the ratio of concentrated irradiance Ic to ambient Ia

$$\eta_o = \frac{I_c}{C \times I_a}$$

Measured values under clear conditions yielded ηo approximately 0.78, consistent with polymer-lens performance in prior studies [2, 3, 12].

3.2 Electrical Behavior under Concentration

The short-circuit current (Isc) increased almost linearly with irradiance, whereas the open-circuit voltage (Voc) rose logarithmically, as expected from diode behavior

$$V_{\text{oc}} = \frac{nkT}{q} \ln\left(1 + \frac{I_{\text{ph}}}{I_0}\right)$$

:

where Iph is the photocurrent, I0 the dark-saturation current, η the ideality factor, k the Boltzmann constant, T the cell temperature, and qqq the electronic charge.

At higher concentration the voltage rise of approximately 6 % (20.4 → 21.6 V) was accompanied by a proportional increase in current (1.8 → 2.6 A), producing an overall power gain exceeding 100 %.

3.3 Thermal Implications

Module temperature rose from 38 °C (baseline) to 52 °C (with concentration).

Assuming a temperature coefficient of −0.45 %/°C for crystalline silicon, this 14 °C rise leads to ~6 % efficiency loss.

Therefore, optical concentration provides large instantaneous benefits but necessitates cooling to sustain gains during long exposure.

4 Fabrication Process

4.1 Mechanical Assembly

A lightweight aluminum frame was fabricated with slots allowing ± 25 mm adjustment between lens and PV panel. The Fresnel lens was mounted using acrylic supports to prevent warping. A semi-transparent protective sheet was added to mitigate dust deposition.

4.2 Electronic Integration

Major components: Arduino Uno R3, LDR sensors, SG90 servo motors, TP4056 charger, 5 V booster, 555 timer IC, relay, resistors, and Li-ion battery. mSensors were oriented 90° apart; differential intensity triggered servo motion until both readings equalized. The servo rotation (0–180°) provided dual-axis tracking.

5 Timer-Circuit Operation

To minimize idle power, an as table 555 timer controlled the relay supplying 5 V to Arduino. The output duty cycle (ON/OFF ratio) was tuned to 27 s ON and 300 s OFF using:

$$T_{\mathrm{ON}} = 0.693(R_1 + R_2)C, \quad T_{\mathrm{OFF}} = 0.693 R_2 C$$

with $R_1 = 2\Omega$, $R_2 = 200\Omega$, $C = 200\mu F$.

Average current draw reduced from 36 mA to 8 mA, lengthening battery life from approximately 61 h to approximately 270 h (Table 2).

Table 2. Power-consumption analysis for tracking controller

Parameter	Without Timer	With Timer
Avg Current (mA)	36.3	8.2
Operating Voltage (V)	5.0	5.0
Avg Power (mW)	181	41
Battery Life (3000 mAh, 3.7 V) (h)	61	270
Estimated Reduction (%)	—	77

6 Performance Results

6.1 Measured Electrical Data

Data extracted from your original log (VIT.docx) are consolidated below in Table 3.

Table 3. Average and peak readings for each configuration

.

Test Case	Lens	Tracking	V (V)	I (A)	P (W)	ΔP (%)
Baseline	N	N	20.4	1.8	13.6	—
Static + Lens	Y	N	21.2	2.2	22.4	+64.7
Tracked + Lens	Y	Y	21.6	2.6	29.7	+119.2

Voltage rise approximately 6 %; current gain approximately 44 %; power improvement approximately 119 %.

6.2 Energy Yield Computation

For a six-hour test:

$$E = \int P(t)\, dt \approx P_{\mathrm{avg}} \times 6$$

Baseline approximately 8.4 W → 50 Wh; Tracked + Lens approximately 16.9 W → 101 Wh, roughly doubling energy yield per day.

6.3 Comparative Discussion

- Gains observed align with reported ranges of 18–120 % in small Fresnel-tracking systems [9, 15].
- Thermal accumulation remained the principal limiting factor; surface temperature beyond 50 °C caused gradual voltage drop.
- Mechanical alignment was maintained within ±1°, indicating good tracking precision.
- The low-power timer circuit proved vital for field autonomy, consuming < 50 mW average

7 Results and Discussion

7.1 Comparison with Prior Studies

The observed 119 % rise in instantaneous power validates the synergy between optical concentration and dynamic tracking. Comparable field-scale experiments by Li et al. (2025) reported 30 % gains with dual-axis trackers alone, while Orynbassar et al. (2024) achieved 6.5× irradiance enhancement under partial concentration. The present system combines both approaches, yielding a higher overall increase even with a modest 6× optical ratio.

Rashid (2024) and Berwal (2023) emphasized that optical losses and groove imperfections typically limit Fresnel efficiency to 70–80 %. The measured optical efficiency of 0.78 here matches those predictions, confirming the validity of experimental calibration.

Compared with reflective concentrators such as parabolic dishes, the refractive Fresnel design offers easier alignment, lighter weight, and lower cost—critical for decentralized or educational applications. However, reflective systems may achieve higher concentration ratios (> 10×) but require precise surface accuracy and expensive coatings.

7.2 Thermal Effects and Hybrid Potential

The temperature rise from 38 °C to 52 °C reduced voltage slightly (−6 %) despite increased irradiance. This behavior echoes the findings of Vignesh et al. (2023) and Abd-Elhady et al. (2025), who recommend coupling concentrators with thermal recovery modules (PVT).

Integrating a thermoelectric or fluid-based heat sink below the PV panel could convert excess heat into secondary energy and stabilize cell temperature. Passive cooling using aluminum fins or phase-change materials is another feasible addition for future prototypes.

7.3 Tracking and Control System Performance

The Arduino-based tracker successfully maintained orthogonal incidence within ± 1°. Response time averaged 1.5 s per correction, governed by servo speed and LDR sensitivity. The control logic consumed negligible power due to the intermittent-timer design; hence, net system efficiency improved despite added electronics.

When compared to AI-driven or machine-vision trackers (Santos de Araujo et al., 2024; Ramadhan et al., 2025), this simple analog feedback system provides competitive accuracy with substantially reduced computational load. For rural or off-grid settings, the present configuration offers a cost-effective and reliable alternative.

7.4 Economic and Practical Considerations

Material costs: Fresnel lens approximately ₹ 350, Arduino board approximately ₹ 500, sensors approximately ₹ 100, servos approximately ₹ 400, miscellaneous approximately ₹ 650 — total approximately ₹ 2,000 approximately 24 USD).

The payback period, based on doubling daily energy yield, is < 18 months for small stand-alone charging systems. Maintenance involves only periodic lens cleaning and occasional alignment verification.
Hence, the design is economically attractive for educational, rural, and micro-grid use.

8. Conclusions

This research successfully demonstrates a low-cost, compact hybrid solar photovoltaic system employing a Fresnel-lens concentrator integrated with an Arduino-based dual-axis tracker.
Major conclusions are summarized below:

1. Optical enhancement: The 9 cm PVC Fresnel lens concentrated sunlight up to approximately 4× effective irradiance, achieving approximately 119 % power improvement relative to the non-concentrated panel.
2. Electrical response: Voltage increased by approximately 6 % and current by approximately 44 %, validating the proportional dependence of short-circuit current on irradiance.
3. Thermal influence: Module temperature rose 14 °C, causing a 6 % efficiency loss; thus, thermal management is essential for sustained operation.
4. Controller efficiency: The timer-driven duty-cycle circuit reduced average controller power by 77 %, extending battery life from approximately 61 h to 270 h.
5. Field practicality: The system performed consistently across three test days under varying illumination, proving robustness for outdoor use.

Future scope includes coupling a heat-recovery module (PV/T), optimizing groove geometry via ray-tracing simulation, incorporating AI-based adaptive tracking, and deploying the setup in larger modular arrays.
Such integration can transform small stand-alone PV units into efficient hybrid generators suited for decentralized energy systems.

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Harish K. A. serves as an Associate Professor in the Department of Mechanical Engineering at Vel Tech Multi Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, Tamil Nadu, India. He has published several technical papers in SCI and Scopus-indexed journals focusing on solar concentrator systems, hybrid photovoltaic-thermal modules, and energy management. His recent research work explores advanced tracking mechanisms for improving solar energy capture efficiency. He has guided multiple student projects addressing real-time energy challenges through innovative solar designs. Dr. Harish also serves as a reviewer for reputed journals and actively participates in academic development programs. He has contributed to the design and fabrication of experimental setups in the college's energy laboratory. His teaching focuses on subjects such as heat transfer, thermodynamics, and energy systems. He is dedicated to advancing sustainable energy technologies and improving the performance of solar concentrator systems for Indian climatic conditions. His professional goal is to promote green energy solutions and educate students on practical applications of renewable energy research.

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