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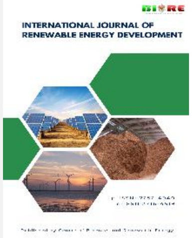

Research Article

Experimental investigation of photovoltaic-thermoelectric hybrid systems enhanced by a heatsink and radiation reflector

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Abstract. This study presents the design and performance evaluation of a hybrid photovoltaic-thermoelectric (PV–TEG) power generation system enhanced by the integration of a heat sink and a radiation reflector under various thermal-management conditions. The primary objective was to investigate the combined effect of these two methods on power output and system efficiency without expanding the PV installation area. The experimental setup encompassed five configurations (A–E), including natural convection, integration of thermoelectric modules, addition of reflective panels, and active cooling using air suction or forced air ventilation. Results demonstrate that all PV–TEG configurations yielded higher power outputs and greater efficiencies than the standalone PV system. Notably, configuration E, which combined radiation reflection with forced-air cooling, achieved the highest performance, increasing the electrical output by approximately 1.27 watts and reaching a peak efficiency of approximately 28.6%. The integration of TEG modules contributed an additional maximum of 2.2% to the total energy output by harvesting the excess thermal energy. Further analysis revealed significant correlations between solar irradiance, temperature, and electrical efficiency. These results highlight the potential of PV–TEG hybrid systems to effectively harness both solar and thermal energy, particularly in high-temperature and high-irradiance environments.

Keywords: electrical efficiency, radiation reflector, photovoltaic power, experimental data, solar radiation

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1. Introduction

In response to rising global energy demand and the urgent environmental challenges associated with fossil fuel reliance, the advancement of clean and renewable energy technologies has become a critical focus of scholarly investigation (Mahdavi *et al*., 2022). In response to rising global energy demand and the urgent environmental challenges associated with fossil fuel reliance, the advancement of clean and renewable energy technologies has become a critical focus of scholarly investigation (Cuce *et al.,* 2024). In response to rising global energy demand and the urgent environmental challenges associated with fossil fuel reliance, the advancement of clean and renewable energy technologies has become a critical focus of scholarly investigation (Elbreki *et al.,* 2021; Qasim *et al.,* 2023). Photovoltaic–thermoelectric (PV–TE) hybrid systems have emerged as a promising approach to mitigate this constraint (Lv, Feng, *et al.,* 2024). In such systems, thermoelectric generators (TEGs) transform thermal gradients into electrical energy via the Seebeck effect (Lotfi *et al.,* 2022). Hybrid designs rely on heat sinks and solar-radiation reflectors to ensure effective thermal management. These components improve the temperature gradient across the TE module, thereby enhancing the energy conversion efficiency (Faridah *et al.,* 2025; Shoeibi *et al.,* 2023). Consequently, PV–TE hybrid systems incorporating heat sinks and reflectors require careful design and performance evaluation to maximize their energy yield (Lv *et al.,* 2025). Despite these benefits, limited studies have systematically examined the combined effects of heat sinks and radiation reflectors within integrated PV–TE systems (Hanani *et al.,* 2023; Y. Wang *et al.,* 2024). To address this gap, the present study establishes an experimental framework to investigate the performance of a PV–TE hybrid configuration incorporating heat sinks and reflective surfaces (Sripadmanabhan Indira *et al.*, 2022). The experimental method quantifies thermal distribution, electrical output, and energy conversion efficiency under different operating conditions (Baccoli *et al.,* 2021; Wang *et al.,* 2025). The primary objective is to examine how passive cooling and radiation redirection mechanisms maximize solar to electric energy conversion efficiency (Bayusari *et al.,* 2025; Saleh, Johar, Jumaat, Rejab, & Jamaludin, 2021). Furthermore, this study offers critical insights into the thermodynamic behavior of hybrid PV–TE systems (Moshwan *et al.,* 2025; Utomo *et al.,* 2023), contributing to the development of advanced thermal management solutions for next-generation renewable energy applications (Kandil *et al.*, 2023; Li, Yu, Peng, *et al.,* 2025; Xian-long *et al.,* 2025). These findings support the development of high-efficiency PV–TE systems for large industrial installations

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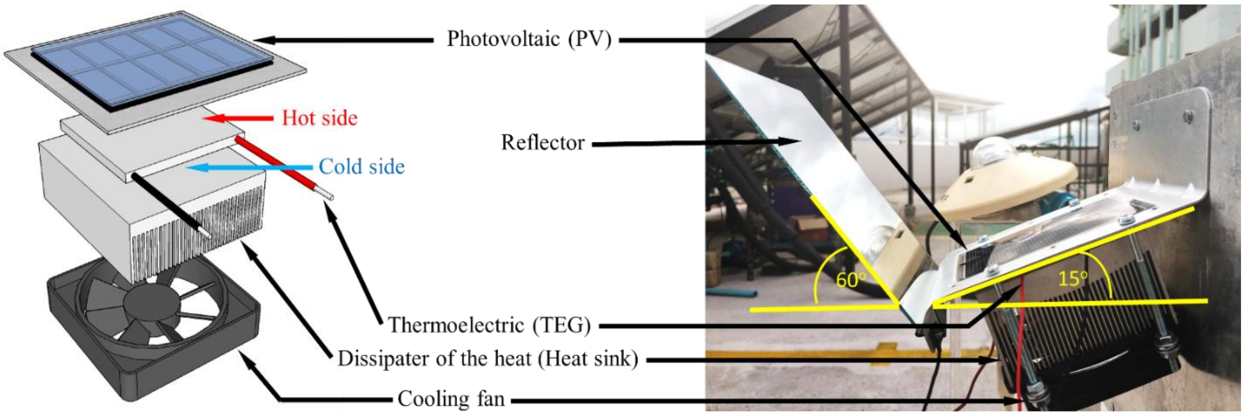
and distributed energy networks (Bulat *et al.,* 2024; Gao *et al.*, 2023). As communities and industries seek fossil fuel alternatives, research on renewable energy technologies has advanced (Kabbani & Honnurvali, 2021). This study builds on existing knowledge to address practical implementation challenges associated with hybrid PV–TE systems in real-world operating conditions (Al-Ghezi et al., 2022; Harmailil *et al.,* 2024; Li, Yu, Zhou, *et al.,* 2025). Recent studies have explored the thermoelectric integration potential of solar harvesting systems (Ahmed *et al.*, 2025; Li, Yu, Peng, *et al.,* 2025; Li, Yu, Zhou, *et al.,* 2025); however, comprehensive experimental studies evaluating system-level interactions between PV modules, TEGs, heat sinks, and optical augmentation techniques under various environmental conditions remain limited (Mustafa *et al.,* 2024). Notably, a substantial portion of the current literature focuses on simulation-based thermal modeling or the performance of isolated components, with limited validation through rigorous empirical testing (Ibrahim *et al.,* 2025; Moshwan *et al.*, 2025). Given the global demand for sustainable energy and the limitations of conventional photovoltaic (PV) systems, systematic evaluation of key performance indicators for PV–TE hybrid systems incorporating heat sinks and radiation reflectors is crucial. PV–TE hybrid systems are integrated configurations in which TEGs convert thermal gradients from PV modules into electrical energy, while heat sinks and radiation reflectors maintain optimal operating temperatures (Hong *et al.*, 2022; Mahmoud AL Shurafa et al., 2024). In this context, electrical efficiency, thermal dissipation, and spectral management are crucial for system performance and design optimization (Guo & Huai, 2023; Lv *et al.,* 2023). Accordingly, hybrid efficiency, energy yield, temperature coefficients, and the levelized cost of electricity (LCOE) are evaluated to determine the economic outcomes (Abhishek Kumar Singh, 2025; Ismaila *et al.,* 2021). This study builds upon a structured review of research on PV–TE hybrid systems incorporating heat sinks and radiation reflectors to establish a robust analytical framework. To achieve a comprehensive system evaluation, the analysis integrates insights from modeling, experimental, and theoretical studies to identify best practices, performance trade-offs, and relevant standardized metrics (Nazri *et al.,* 2023; Yang *et al.,* 2024). Building on this foundation, the present work employs a systematic and replicable experimental methodology to capture real-time thermoelectric behavior and bridge the gap between theoretical potential and practical system design (Alajlan *et al.,* 2024; Bayusari *et al.,* 2025). The study investigates the synergistic interaction between passive radiative elements and conductive cooling mechanisms in enhancing localized heat dissipation and overall PV–TE performance. Performance indicators, including transient temperature differentials, power density variation, and efficiency coefficients are integrated to analyze system behavior under high solar irradiance and elevated ambient temperature environments. The findings contribute to the advancement of passive energy enhancement methods aimed at simplifying systems and optimizing their output. Ultimately, this work supports the development of compact, low-maintenance, and scalable hybrid systems suitable for off-grid applications. It further informs the design principles of integrated renewable systems aligned with global sustainability objectives and energy equity initiatives.

2. Methodology

2.1 Description of the experimental setup

The experimental configuration of the PV–TEG hybrid power generation system is shown in Figure 1(A). The system was designed to evaluate the energy conversion efficiency under conditions of enhanced solar irradiation and thermal management conditions. The photovoltaic (PV) panel was positioned at a 15-degree tilt angle to enhance solar energy absorption. A radiation reflector was positioned at a 60-degree angle adjacent to the PV module to redirect additional sunlight onto the panel surface to enhance solar exposure.

The TEG modules were mounted on the underside of the PV panel, with the hot side in direct contact with the panel backside. The cold side of the TEG was connected to a heat sink equipped with a cooling fan. This setup promoted forced convection, which accelerated heat dissipation from the cold side, ultimately enhancing the temperature difference (ΔT) across the TEG module. An increase in ΔT directly enhanced the electrical power generation capabilities of the TEG unit. The integrated design improved the energy conversion efficiency of the system by effectively harnessing both solar and thermal



(A)

(B)

Fig. 1 Schematic diagram of the PV–TEG Hybrid Power Generation System incorporating a Radiation Reflector and Cooling Fan.

Table 1
Specifications of the PV and TE modules.

Characteristic	Specification
PV model dimensions (Mono-crystalline Silicon Type; 6V, 1W), (mm × mm × mm)	55×85×0.2
TE module (Model type: TEG1-12610-4.3), (mm^3)	40×40×4
Radiation reflector (Material is mirror), (mm × mm × mm)	80×90×0.4
Heat Sink (Material is aluminum), (mm × mm × mm)	70×70×50

energy sources while maintaining the same spatial footprint of the PV array, as shown in Fig. 1(B).

2.2 Mathematical background

The electrical efficiency of a PV module is defined as the ratio of electrical output power to incident solar input power. Based on the first law of thermodynamics, which governs energy conservation, the PV electrical efficiency can be expressed as: (Congxiang *et al*., 2025; Tyagi *et al.,* 2023)

$$\eta_{\mathrm{e-PV}} = \frac{P_{out}}{P_{in}} \tag{1}$$

The output power of the PV module (P_{out}) was calculated from the measured voltage (V_{PV}) and current (I_{PV}) values recorded by the data logger, using the following relation: (Khenfer *et al.*, 2024; Teffah & Zhang, 2017)

$$\mathrm{P_{out}} = V_{PV} \times I_{PV} \tag{2}$$

Furthermore, the input power (P_{in}) to the PV module is the energy received from solar radiation and can be calculated as: (Saleh, Johar, Jumaat, Rejab, & Wan Jamaludin, 2021)

$$P_{in} = A_{PV} \times G_T \tag{3}$$

where A_{PV} represents the effective PV cell area (m^2), and G_T denotes local solar irradiation (W/m^2). Notably, the area specified by the dimensions in Table 1 was be adjusted using the manufacturer-provided packing factor to determine the effective PV cell area. Accordingly, the electrical efficiency of the PV module (η_{e-PV}) was calculated as (Montero et al., 2025; Sheikholeslami *et al.,* 2024; Xian-long *et al.,* 2025)

$$\eta_{\mathrm{e-PV}} = \frac{V_{PV} I_{PV}}{A_{PV} G_T} \tag{4}$$

The electrical efficiency of the TE module can be determined using the following equation: The conversion efficiency of the TE module was calculated as follows: (Ahmed et al., 2025; Lv, Zhang, et al., 2024)

$$\eta_{\mathrm{e-TE}} = \eta_{\mathrm{C}} \frac{M-1}{M+(\mathrm{T_c}/\mathrm{T_h})} \tag{5}$$

where T_h and T_c represent the temperature at the hot and cold side of TE module, respectively, $M = 1+ZT_m$ where $T_m = 0.5(T_h + T_c)$ the mean temperature of the TE module, Z is the figure of merit of the TE material ($Z = 2.6\times10^{-3}$ 1/K) (Bamroongkhan & Nararom, 2024), and η_c is the Carnot efficiency; $\eta_c = (\Delta T/T_h)$, $\Delta T = T_h - T_c$ represents the temperature difference between the hot and cold sides of the TE modules. The electrical output power of the TE module (P_{TE}) was determined from the measured voltage using the following equation: (Rahman *et al.,* 2024; Wicaksono *et al.,* 2018)

$$\mathbf{P_{TE}} = \boldsymbol{V_{TE}} \times \boldsymbol{I_{TE}} \tag{6}$$

where I_{TE} represents the output current of the TE module, and V_{TE} denotes the output voltage of the TE module.

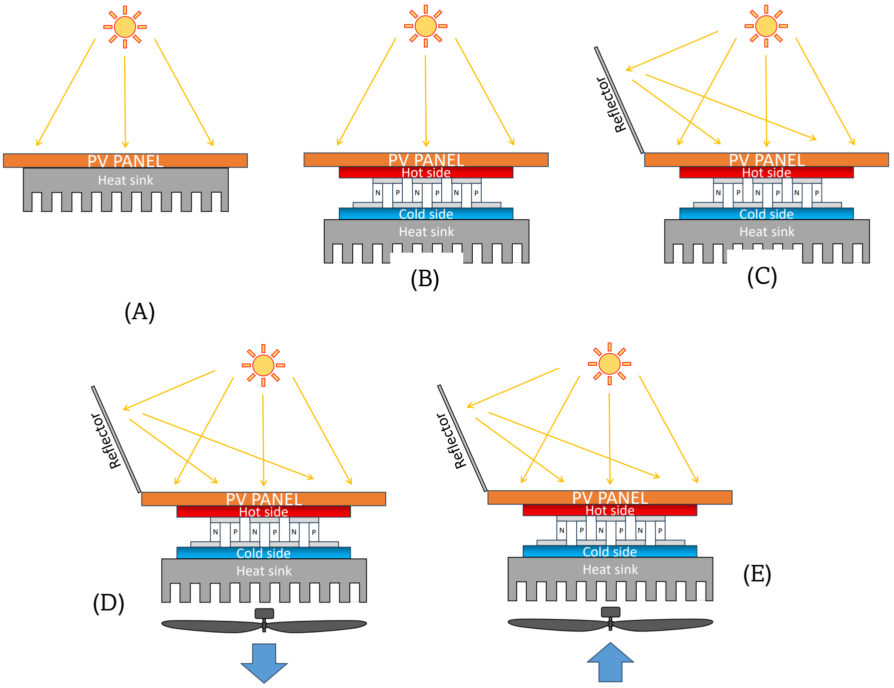


Fig. 2 Experimental Conditions for Thermal Management.

Table 2
Operating configurations and thermal management conditions for the PV–TEG hybrid system.

Configuration	Reflector Usage	TEG Usage	Thermal Management Method	Key Characteristics
(A)	Not used	Not used	Natural convection	Baseline thermal control system
(B)	Not used	Used	Natural convection	Initiates thermal-to-electric energy conversion via TEG
(C)	Used	Used	Natural convection	Enhances irradiance on PV panel for increased output
(D)	Used	Used	Active air suction (bottom side)	Improves heat dissipation from cold side for enhanced cooling
(E)	Used	Used	Forced air convection (bottom side)	Maximizes active heat removal efficiency

2.3 Experimental tests

Cooling techniques for PV–TEG hybrid systems: Experimental configurations Five experimental configurations (A–E) were designed, as shown in Fig. 2, each incorporating a distinct combination of cooling methods and solar irradiance enhancement technique. The objective was to assess how different temperature control mechanisms affect the overall performance of the PV–TEG hybrid system, particularly in terms of its electrical output and thermal regulation. These strategies were implemented optimize the surface temperature for power generation and reduce system heat. Table 2 summarizes the experimental conditions used in this study.

Configuration A: Natural Convection Cooling

The baseline configuration involved mounting the PV panel directly onto a heat sink without additional thermal management components. Heat dissipation occurred through natural convection and thermal diffusion from the heat sink to the surrounding environment.

Configuration B: TEG + Natural Convection

In this configuration, a TEG module was installed between the PV panel and the heat sink. The TEG converts the temperature gradient into electrical energy via the Seebeck effect. Heat dissipation occurred through natural convection, sustaining the temperature difference across the TEG and thereby enabling thermoelectric power generation.

Configuration C: Reflector + TEG + Natural Convection

In this configuration, a reflective surface was introduced to intensify the solar irradiance directed onto the PV panel, thereby increasing power generation. However, the enhanced solar input also increased the panel surface temperature, particularly on the hot side of the TEG. This increase in temperature amplified the thermal gradient across the TEG (between its hot and cold sides), which, in turn, boost the power generation efficiency.

Configuration D: Reflector + TEG + Active Air Suction

Building upon configuration C, this setup incorporated an air suction fan positioned beneath the heat sink to actively facilitate heat removal from the cold side of the thermoelectric generator (TEG). This enhanced heat dissipation effectively reduced the temperature on the cold side, thereby increasing the ΔT across the TEG and enhancing its electrical output.

Configuration E: Reflector + TEG + Forced Air Convection

In this configuration, air suction was replaced with forced air injection, similar to configuration D. A fan directed ambient air onto the underside of the heat sink. This active cooling strategy enhanced heat removal from the cold side of the TEG, boosting ΔT and its energy conversion efficiency.

The five configurations were systematically developed to isolate and analyze the individual and combined effects of reflective surfaces, thermoelectric integration, and cooling methods on the performance of the PV–TEG hybrid energy system.

3. Results and discussion

3.1 Variations in Solar Irradiance, Temperature and Wind Speed.

The experimental data for the key environmental parameters are shown in Fig. 3. Solar irradiance began at approximately 220 W/m^2 at 7.30 AM, progressively rising to a peak of nearly 920 W/m^2 between 11.30 AM and 1.00 PM. It then gradually decreased, to below 220 W/m^2 by 5:30 PM. The solar irradiance profile followed a parabolic curve that was almost symmetrical, consistent with clear-sky conditions. The highest intensity occurred at solar noon. The PV panel surface temperature increased from approximately 30.6 °C in the early morning to approximately 71.4 °C between 12:00 and 1:00 PM, before decreasing to approximately 31 °C by 5:30 PM. The PV panel temperature remained consistently higher than the ambient temperature throughout the day, particularly at noon. This thermal accumulation reduces power conversion efficiency, as PV efficiency typically declines with increasing operating temperature. The rise in operating temperature is primarily driven by higher solar irradiance. Ambient temperature increased from 30.5 °C at 7:30 AM to a peak of approximately 37.8 °C at 12:00 PM, and then slowly decreased. The elevated ambient and surface temperatures indicate that the PV system operated under thermally demanding conditions on the test day. Wind speed ranged from 0.53 to 1.37 m/s between 7:30 AM

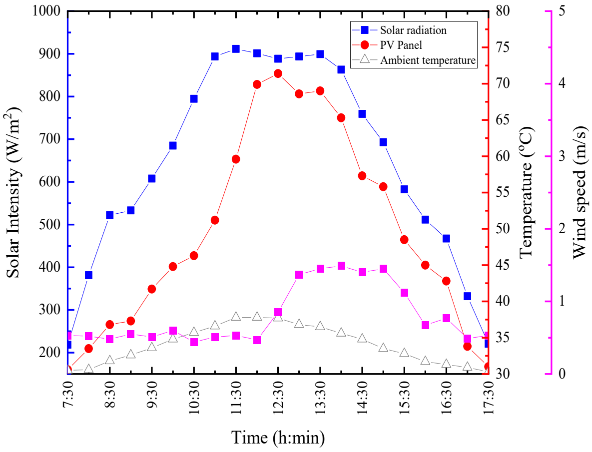


Fig. 3 Influence of environmental conditions on PV panel performance over the course of the day.

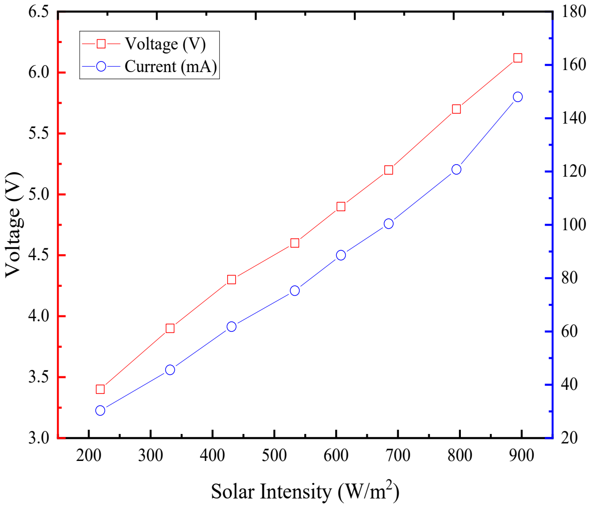


Fig. 4 Voltage and current characteristics of the photovoltaic cell under varying solar irradiance conditions.

to 1:00 PM, peaking at 1.49 m/s between 1:30 and 14:00 PM before declining. Wind enhances convective heat transfer at the PV surface, facilitating heat dissipation. The increased wind speed during the afternoon likely contributed to partial moderation of panel temperatures.

3.2 Effect of Solar Irradiance on the Voltage and Current Characteristics of the Photovoltaic Cell.

Fig. 4 illustrates the influence of varying solar irradiance levels on the electrical behavior of the PV, specifically its voltage and current output. The voltage output increased from approximately 3.4 V at an irradiance of 218.61 W/m^2 to approximately 6.12 V at 893.77 W/m^2. The voltage rise was particularly steep between 380 and 385 W/m^2, after which it began to plateau with in the 800-900 W/m^2 range. This trend suggests that the voltage increases with irradiance but approaches a saturation point at higher irradiance levels. In contrast, the current output increased from approximately 30.3 mA to approximately 148 mA as irradiance increased. This growth followed a quasi-linear trend with no evident saturation, even at higher irradiance levels. The generated current increased proportionally with the incident photon flux as the solar radiation intensity increased. Thus, the PV cell current exhibited a stronger linear dependence on solar irradiance than voltage. Under high-irradiance conditions, the voltage approached a saturation value, whereas the current continued to scale proportionally with light intensity (Fig. 4).

3.3 Effect of Solar Intensity on Power Output and Efficiency of the PV Cell.

As illustrated in Fig. 5, the experimental results demonstrate the relationship between incident solar irradiance and both the electrical power output and energy conversion efficiency of the PV panel. The power output increased from approximately 0.57 W at an irradiance of 218.61 W/m^2 to about 0.98 W at 893.77 W/m^2, following a nonlinear upward trend. The convex profile of the curve reflects the strong and responsive behavior of the PV panel to increasing light intensity. No evidence of performance saturation was observed in this irradiance range, suggesting that power generation continued to rise as the irradiance increased.

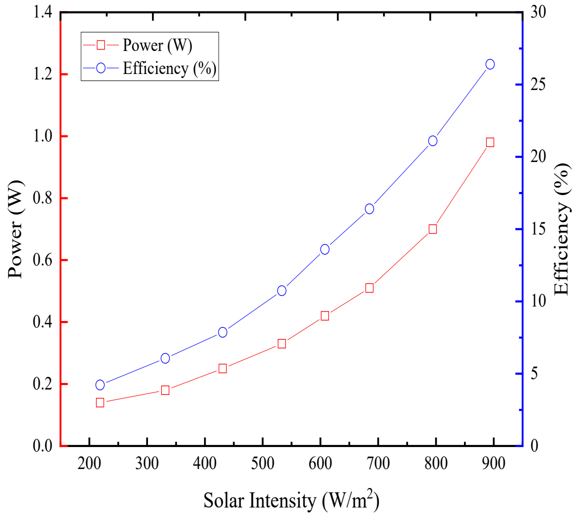


Fig. 5 Power Output and Conversion Efficiency of the Photovoltaic Panel.

In terms of efficiency, the PV system exhibited a conversion efficiency of approximately 8.47% at 218.61 W/m^2, gradually increasing to approximately 26.4% at 893.77 W/m^2. Beyond this point, the efficiency curve approached plateau, stabilizing between 800 and 900 W/m^2 at a maximum efficiency of approximately 27%. This plateau indicates that the panel reached its practical conversion limit within the tested conditions, even though the power output continued to rise with increasing irradiance. According to photovoltaic energy conversion theory, efficiency increases with irradiance up to a threshold, beyond which it approaches a limiting value. High irradiance levels flatten the efficiency curve, suggesting the presence of other constraints such as high PV panel temperatures. The reported efficiency and power values are influenced by unavoidable uncertainties in temperature, irradiance, and electrical measurements, particularly at the low power levels associated with thermoelectric generators. However, identical sensors and measurement protocols were used across all configurations. Consequently, these uncertainties do not compromise the relative performance comparisons, and the observed trends and system ranking remain reliable.

3.4 Comparison of Power Output and Efficiency of Standalone Photovoltaic Systems and PV–TEG Hybrid Systems.

Fig. 6 compares the power output and energy conversion efficiency of the conventional PV and the hybrid PV–TEG systems under all experimental conditions (configurations A–E). Both systems exhibited progressive increases power output from configuration A to E. However, the PV–TEG configuration consistently produced higher power than the standalone PV system under all test conditions, albeit with modest differences. The integration of a TEG resulted in a measurable and stable increase in total power output by recovering the thermal energy that would otherwise have beend dissipated into the environment.

In addition, the efficiency trends revealed that the PV–TEG system achieved a higher overall energy conversion efficiency than the conventional PV system across all experimental conditions. This improvement can be attributed to the Seebeck effect, whereby the temperature gradient across the TEG

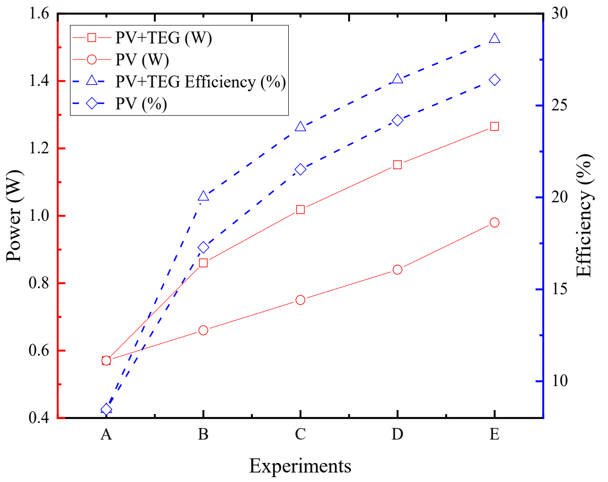


Fig. 6 Power output and conversion efficiency of standalone PV and PV–TEG hybrids systems across experimental configurations.

enables additional electrical power generation. Moreover, the presence of the TEG contributes to partial thermal regulation of the PV module, thereby mitigating temperature-induced efficiency losses. Consequently, the combined PV–TEG system enhanced total energy utilization and demonstrated its potential as an effective hybrid approach for improving photovoltaic performance under high-temperature or high-irradiance operating conditions.

In terms of energy conversion efficiency, the PV–TEG system consistently outperformed the standalone PV system in all the experimental setups. The efficiency of the hybrid system improved steadily from approximately 8.47% in configuration A to approximately 28.6% in configuration E. The near-linear efficiency trend of the PV–TEG system indicates stable system behavior and consistent experimental conditions throughout the study. Each experimental configuration showed a 3-4% increase in electrical output attributable to the TEG modules. Under high-temperature conditions, the TEG effectively converted excess heat to electricity, enhancing this improvement. The consistently positive contribution of TEG integration across all configurations confirms its viability as an additional energy-harvesting technology. Table 3 presents the quantitative results of these experiments. The efficiency gain is amplified when thermal management strategies actively regulate the heat flow. Forced air convection not only limits excessive temperature increases in PV cells but also promotes directional heat transfer toward the TEG, reducing uncontrolled thermal dissipation to the surroundings. Consequently, the hybrid system approaches a more balanced operating condition, where electrical and thermoelectric conversions coexist synergistically rather than competitively.

3.5 Comparison of Power Outputs of Photovoltaic and Thermoelectric Systems.

Fig. 7 shows the power output of the PV panel and thermoelectric generator over time. The PV output increased from 0.12 W in the morning to 0.98 W at 1.00 PM, then gradually decreased to 0.1 W by 5.30 PM. The resulting power curve was symmetrical and parabolic, reflecting solar irradiance daily profiles.

In contrast, the TEG exhibited a relatively low initial output of 0.05 W, rising to a maximum of 0.29 W at approximately at around 1.00-1.30 PM, coinciding with the PV peak. The TEG power output is directly influenced by the thermal gradient, which arises from the temperature difference between the rear surface of the PV panel and the ambient air. An in-depth analysis of the 4.5 hour window between 11.00 AM and 3.30 PM identified this period as the optimal timeframe for both PV and TEG power generation. This interval is particularly significant for system design considerations related to energy storage and cumulative energy yield estimation. Although the PV unit is the principal contributor to electrical power, delivering a peak output of up to 0.98 W, the TEG plays a supportive role in energy recovery by converting excess heat into electrical energy. The TEG harvests synchronous thermal energy from surplus solar energy that the PV system cannot directly convert into electricity. This shows that improved TEG technology can boost energy system efficiency, especially during midday when thermal gradients are at their highest. The integration of improved TEG technology therefore presents a viable pathway for more effective waste heat utilization in future hybrid solar energy systems.

Despite the observed performance improvements, the experimental configuration presents several drawbacks. The use of small-scale PV modules limit the power output and may affect

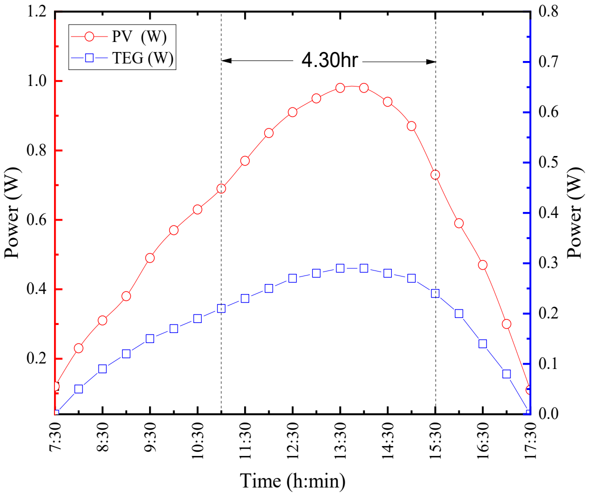


Fig. 7 Photovoltaic and thermoelectric power outputs over time.

Table 3
Summary of Experimental Results.

Configuration	PV Power (W)	PV+TEG Power (W)	PV Efficiency (%)	PV+TEG Efficiency (%)
(A)	0.57	0.57	8.47	8.47
(B)	0.66	0.86	17.28	20.1
(C)	0.75	1.02	21.53	23.8
(D)	0.84	1.16	24.2	26.4
(E)	0.98	1.27	26.4	28.6

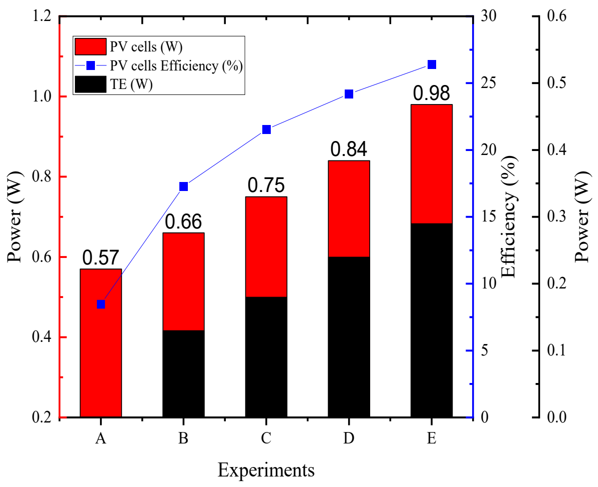


Fig. 8 PV and TEG Energy Output Comparison by Configuration.

the thermal behavior of the system, as convective cooling tends to be more effective at smaller scales due to higher surface area-to-volume ratios. Consequently, the efficiency gains achieved under laboratory conditions may not translate linearly to utility-scale PV–TEG systems without careful thermal design optimization. Moreover, the contribution of the thermoelectric generator remains constrained by limited temperature gradients and the relatively low conversion efficiency of commercially available thermoelectric materials. Increasing thermoelectric output would generally require larger temperature gradients, which may elevate PV operating temperatures and thereby reduce photovoltaic efficiency or compromise long-term system reliability. Forced air convection also requires power to operate the cooling fan, which is not included in the net energy balance and could partially offset the reported gains, especially in low-power applications. As a result, further research is needed on long-term operation, environmental degradation, and maintenance effects, as this study only examined short-term performance under specific environmental conditions.

3.6 Comparative power evaluation of photovoltaic and thermoelectric systems under different experimental conditions.

As shown in Fig. 8, the comparative analysis indicates that the PV system remained the primary contributor to total power generation, accounting for approximately ~97% of the total output. In contrast, the TEG contributed only in the milliwatt range; however, its power output exhibited a consistent upward trend across all configurations (A–E). The conversion efficiency of the PV system improved from approximately 8.47% in configuration A to approximately 26.4% in configuration E, indicating the strong influence of environmental and experimental parameters, particularly temperature and solar irradiance, on system performance. The total energy of the integrated PV+TEG system increased progressively from configuration A to E, as detailed in Table 3. This trend reflects the effectiveness of the combined system in enhancing overall system performance. These experimental results are consistent with those of previous studies (Alinia & Sheikholeslami, 2025; Kangiwa et al., 2024). Although the TEG contributes a relatively small portion of the total power, it demonstrates the tangible potential for recovering excess heat from PV panels. The observed steady increase in PV efficiency may be attributed to more effective thermal management or improved irradiance characteristics during the experiment.

The hybrid PV–TEG system thus possesses the capacity to harvest both solar and thermal energy. Although the TEG contributes minimally to the total power generation, it significantly augments the energy yield of the system by a measurable percentage. Such hybrid configurations are particularly well suited to high-irradiance, high-temperature environments where excess heat is abundant.

The novelty of this study lies in its system-level experimental evaluation of the combined thermal management and radiation enhancement in a PV–TEG hybrid configuration. Multiple cooling modes were evaluated and directly compared under identical conditions, unlike previous studies that examined cooling or thermoelectric integration in isolation. This unified framework makes it easy to see how airflow mechanisms influence overall system performance. The experimental results confirmed that forced air convection provides a dual benefit by reducing the PV temperature while sustaining a useful temperature gradient across the TEG. The findings collectively indicate that moderate thermoelectric integration, in conjunction with enhanced thermal and radiative management, can produce consistent and practically significant efficiency improvements.

4. Conclusions

This study presents the design and evaluation of a hybrid power generation system integrating PV modules with TEGs under improved thermal and radiation management conditions. The experimental design included radiation reflectors and various cooling methods, including natural convection, air suction, and forced air blowing, to optimize the system thermal environment. Five different experimental settings (A–E) were used, each showing different degrees of electrical output and energy conversion efficiency, depending on the applied cooling strategy used. The results indicate that integrating a TEG into a PV system consistently improved the total electricity output. In particular, configuration E, which combined forced air convection and radiation reflection, achieved the highest energy output of 1.27 W and an efficiency of 28.6%. The use of TEGs contributed approximately 2.2% additional energy by converting surplus thermal energy that would otherwise have been dissipated. A clear positive correlation was observed between solar radiation, PV panel temperature, and overall system efficiency. The results demonstrate that effective thermal management, especially through air convection, reduces the surface temperature of the PV panel while increasing the temperature gradient (T) across the TEG module, thus improving the electrical production. This study highlights the practical potential of hybrid energy systems capable of harvesting both photovoltaic and thermal energy within fixed installations. Such systems are particularly suitable for tropical regions with high solar intensities and ambient temperatures. In addition, they offer promising applications in low-power autonomous systems and energy storage integration, representing an important step towards more efficient renewable energy technologies. Moreover, the experimental results demonstrated clear performance improvements for the proposed PV–TEG hybrid system. The integration of the thermoelectric generator consistently enhanced the total electrical output compared to that of the standalone PV module. Among all tested configurations, the combination of radiation reflection and forced air convection delivers the highest performance, achieving 1.27 W of electrical power and a hybrid energy conversion efficiency of 28.6%. This positions it within the upper performance range for flat-plate PV–TEG experimental studies. These quantitative findings demonstrate that PV–TEG hybrid systems can deliver practical performance gains in real-world renewable energy applications, even when the thermoelectric contribution is modest, provided that thermal and radiative management are properly managed.

The results further indicate that PV–TEG hybrid systems, with effective thermal and radiative management, can provide substantial benefits in situations where conventional PV performance is limited by high operating temperatures, particularly in tropical and high-irradiance regions. Although the present study was conducted on a restricted experimental scale, it employed the fundamental approaches of regulated heat extraction and waste-heat recovery that are inherently scalable and may be implemented in larger photovoltaic modules through appropriate thermal design and modular integration. The current study is small-scale, but regulated heat extraction and waste-heat recovery can be applied to larger photovoltaic modules via thermal design and modular integration. Performance gains, energy consumption, system complexity, and cost must be balanced for practical scaling. Future research should focus on comprehensive implementations, extended external evaluations, net energy and techno-economic analyses, low-power cooling techniques, and enhanced thermoelectric materials to facilitate realistic deployment.

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