EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(7), 205–215
https://doi.org/10.12912/27197050/222626
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Received: 2026.05.12
Accepted: 2026.06.15
Published: 2026.07.01

Exergy analysis on solar photovoltaic integrated with thermoelectric cooling system

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ABSTRACT

This study presents an experimental and thermodynamic investigation of a solar photovoltaic (PV) system integrated with a thermoelectric cooler (TEC)-based cooling arrangement. Three configurations were analyzed under identical outdoor conditions: (i) a conventional PV module without cooling, (ii) integrated with a bismuth telluride (Bi_2Te_3) module, (iii) with a lead telluride (PbTe) thermoelectric system. The performance comparison was carried out in terms of temperature reduction, electrical output, exergy input, hybrid system exergy efficiency (HSEE), and hybrid system exergy destruction (HSED). Experimental results indicate that the integration of thermoelectric materials significantly reduces the operating temperature of the PV module. The module with Bi_2Te_3 exhibited the lowest peak surface temperature (51.4 ± 1.0 °C) compared to the conventional system (55.6 ±1.0 °C) and the PbTe-based system (53.2 ± 1.0 °C) lies in between. Correspondingly, the net electrical output improved from 8.93 ± 0.27 W (without TEC) to 10.59 ± 0.32 W with Bi_2Te_3 and to 9.63 ± 0.29 W with PbTe, demonstrating enhanced energy conversion performance. Exergy analysis revealed that the hybrid PV-TEC systems possess improved HSEE due to reduced thermal losses and lower entropy generation. The decrease in operating temperature minimizes irreversibilities associated with heat dissipation, thereby reducing HSED. Among the tested materials, Bi_2Te_3 showed better HSEE (15.37% more compared to no TEC), leading to cooling effectiveness. The study confirms that thermoelectric cooling effectively reduces PV operating temperature and enhances PV-side electrical behaviour. However net thermodynamic benefit depends on the trade-off between improved PV output and TEC power consumption. This hybrid approach offers a promising pathway for enhancing the overall performance and sustainability of solar energy systems.

Keywords: solar PV, exergy analysis, thermo-electric, sustainability, renewable energy.

INTRODUCTION

The growing need for clean and sustainable energy has augmented the adoption of solar energy systems, particularly PV technology. Based on the PV effect, PV systems directly convert solar radiation into electrical energy and are widely recognized for their reliability, low maintenance, and environmental benefits (Candra et al., 2022, Gupta et al., 2022). However, a major limitation of PV modules is their relatively low conversion efficiency, which is predominantly affected by operating temperature (Gopinath and Marimuthu, 2024). As the temperature of a PV panel increases, its electrical efficiency reduces, leading to lower power output and lesser overall system performance. A considerable part of solar irradiation is not transformed into electricity but transferred as heat (Ider et al., 2022). This not only elevates the module temperature but also introduces thermodynamic inefficiencies. Conventional energy analysis from first law of thermodynamics provides information on energy quantity but fails to account for energy quality and irreversibility (Golmohammadpour et al., 2026). In contrast, exergy analysis offers a more comprehensive evaluation by quantifying useful work potential and identifying losses due to entropy generation (Al-Tahaineh, 2025). To mitigate thermal losses and enhance PV performance, various cooling techniques have been explored, including passive and active cooling methods. Among these, TEC using materials such as Bi_2Te_3 and PbTe has gained attention due to its compactness, reliability, and ability to manage heat (Montero et al., 2025). Thermoelectric devices operate based on Peltier and Seebeck effects and enable active thermal regulation of PV modules (Li et al., 2017). In this context, the coupling of TECs with PV systems reports a better hybrid approach to enhance both energy and exergy performance. By reducing the operating temperature of the PV module, thermoelectric cooling minimizes entropy generation and exergy destruction, leading to improved electrical output (Rashid et al., 2026, Kumar et al., 2020). Furthermore, the effectiveness of such systems strongly depends on the thermoelectric material used, making comparative analysis essential. Alinia and Sheikholeslami (2025) numerically analysed the performance of solar PV system integrating with TEC module and paraffin-based nanomaterials. They also determined the impact of dust accumulation on the panel on the performance of the PV system. They observed the integration of TEC and nanomaterials significantly enhanced the electrical output. Alktranee and Peter (2023) investigated the impact of aluminium fins and evaporative cooling on the exergy efficiency of solar PV system. They observed that a reduction of temperature of panel of 6.7% leading to 21.3% of increment in output power. Thermodynamic analysis of PV systems coupled with Graphene oxide (GO) hybrid nanofluids with volume concentrations of 0.2, 0.4 and 0.8 g/L and pulsating heat pipe is done by Kargaran et. al., (2024). They observed little enhancement in first-law efficiency. Solar PV coupled with TEC system for cold storages is investigated numerically by Kaushik et. al., (2016) and observed that the developed system is well utilized for storage applications. Sharifpur et.al., (2022) numerically examined the performance of solar PV system with SWCNT-water nanofluid at 0.5% and 1% volume fractions. They observed the exergy efficiency of 15.98% and 16.002% respectively. Shittu et. al., (2020) conducted experiments on solar PV-TEC system using flat plate pipe with micro channel to perform exergy analysis. They observed that the composite system exceedingly performed than PV system alone. Singh et. al., (2024) performed exergy analysis of solar PV-TEC system coupled with mixed mode greenhouse drier for agricultural applications. They observed the enhanced thermal efficiency (overall) reported to be 59% and 70% at 0.01 and 0.02 kg/s mass flow rates respectively. Singh et. al., (2025) conducted experiments on solar PV-TEC air collector coupled with solar dryer and observed the overall thermal efficiency found to be 67.7% and exergy efficiency of 8.2%. Tyagi et. al., (2023) reviewed the developments on solar PV-TEC systems and presented the thorough analysis.

Although several studies have investigated PV-TEC hybrid systems, limited experimental studies have comparatively evaluated Bi_2Te_3 and PbTe thermoelectric cooling modules under identical outdoor operating conditions using an exergy-based framework. Existing works mainly focussed on electrical efficiency enhancement, whereas the present work additionally evaluates irreversibility reduction and exergy destruction characteristics under real climatic conditions. Furthermore, the study targets low-power decentralized PV applications where thermal management remains critical for maintaining stable electrical performance.

MATERIALS AND METHODS

The system comprises a solar PV module of polycrystalline type coupled with and without TEC. The cooling system is designed to reduce the operating temperature of the PV module, so augmenting its electrical efficiency and exergy output. The thermoelectric modules are fabricated generally using semiconductor materials like Bi_2Te_3 and PbTe. Bi_2Te_3 is widely preferred for near-room-temperature thermoelectric applications, whereas PbTe is generally more suitable for medium-to-high temperature thermoelectric operation. However, PbTe was included in the present study for comparative assessment under identical PV cooling conditions. Solar PV module's specifications are presented in Table 1.

EXPERIMENTAL SETUP

Experimental setup is established and tested in Rajam village (N 18.45°, E 83.65°), a southern part of India. Experiments are conducted during the month of April, 2026 from the morning 8:00 AM to 4:00 PM. Solar PV modules of polycrystalline (Nos.3) type as per the specifications shown in Table 1 are used in order to have the same conditions for all the three cases (no TEC, Bi_2Te_3, PbTe). Specifications of Bi_2Te_3, PbTe are presented in Table 2 and Table 3. Each panel is mounted on a rigid test frame. Five thermoelectric cooling modules are placed as shown in Figure 1, on rear side of the PV panel using a thermally conductive interface material (thermal paste). Dimensions of TEC are of 40 × 40 × 4 mm and weight of 35 g. The cold side of the thermoelectric module extracts heat from the PV surface, while the hot side is attached to an aluminium heat sink to dissipate heat into the ambient air. The PV panel operates under solar radiation condition. Solar PV panel is mounted at an angle of 20° for all the experiments. Steady state heat transfer conditions and uniform solar radiation over PV surface are assumed. Contact resistance between PV and TEC module is neglected. Material properties are assumed to be constant. Steps of assembling the setup are shown in Figure 1 and the final experimental setup is represented in Figure 2. Digital pyranometer is used to measure solar irradiation. Setup consists of temperature measurement system in which, the digital temperature indicator is connected through k-type thermocouples to PV panel. It is used to indicate the temperature of solar PV and ambient. Electrical output parameters, including voltage, current, and power, are measured using dedicated solar PV power measurement units. The thermoelectric cooling modules were powered using an external regulated DC power supply. The thermoelectric cooling modules consume electrical energy during operation. Accordingly, both PV-side exergy behavior and net HSEE were evaluated separately to avoid ambiguity in thermodynamic interpretation.

A 10 W polycrystalline module was selected to enable controlled laboratory-scale outdoor experimentation and repeatable thermal characterization. Although the absolute power levels are small, the thermal behavior and exergy trends remain representative for comparative analysis of thermoelectric cooling configurations. Experiment was conducted for 30 days. Average solar irradiation readings of the month duration were taken into consideration for analysis. The standard deviation in output power was observed within ±3%. Statistical comparison indicates that the observed improvement exceeded the

Table 1. Specifications of solar PV module

Parameters	Specifications
Length, Breadth (mm)	300, 350
Thickness (mm)	20
Op-circuit voltage (V)	21.5
Short circuit voltage (A)	0.58
Max. power (W)	10
Max. power voltage V_{mp}, (V)	18
Max. power current I_{mp} (A)	0.55

Table 2. Specifications of TEC module (Bi_2Te_3)

Parameters	Specifications
Length, Breadth (mm)	40, 40
Thickness (mm)	4
Maximum operating temperature (°C)	140
Seebeck coefficient (V/K)	0.2
Weight (g)	35
Open circuit voltage (V)	4.8
Current at 100 °C (A)	0.68

Table 3. Specifications of TEC module (PbTe)

Parameters	Specifications
Length, Breadth (mm)	40, 40
Thickness (mm)	4.2
Seebeck coefficient (V/K)	0.35
Maximum operating temperature (°C)	500
Weight (g)	35
Open circuit voltage (V)	7.2
Current at 300 °C (A)	1.85

experimental uncertainty limits. Exergy is the maximum possible useful work when the system is in equilibrium with the environment. The exergy input associated with solar radiation was evaluated using the Equation 1 (Petela, 1964). This equation is widely adopted for photovoltaic exergy analysis because it accounts for the quality of solar radiation relative to ambient conditions. Convective thermal exergy loss from the PV surface to ambient air was estimated using the exergy associated with convective heat transfer. The convective heat transfer rate was evaluated using Newton's law of cooling, while the corresponding exergy transfer was determined based on the ambient reference temperature. Exergy input is determined from the Equation 1.

$$Exergy\ Input = \\ = A \times G\ (1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}(\frac{T_a}{T_s})^4) \quad (1)$$

where: A is the area of the panel exposed to solar irradiance (m^2), G is solar irradiance (W/m^2), T_a is the temperature of ambient air (K), T_s is the temperature of the sun assumed to be (5777 K).

$$Net\ electrical\ power\ gain = \\ = P_{net} = P_{PV} - P_{TEC} \quad (2)$$

HSEE is determined from the Equation 3.

$$HSEE\ \eta_{ex,hybrid} = \frac{P_{PV} - P_{TEC}}{Ex_{Solar}} \times 100 \quad (3)$$

HSED of hybrid PV-TEC system is determined from the Equation 4.

$$HSED = Solar\ exergy\ input - \\ - (P_{PV} - P_{TEC}) - rejected\ thermal\ energy \quad (4)$$

$$Thermal\ exergy\ loss\ due\ to\ convection = \\ = hA(T_p - T_a)(1 - \frac{T_a}{T_p}) \quad (5)$$

where: h is natural convective heat transfer cefficient assumed as 8 W/m^{2}K, T_p is the surface temperature of panel (K).

EXPERIMENTAL UNCERTAINTY

Here is the uncertainty analysis Table 4 for the instruments typically used in solar PV and

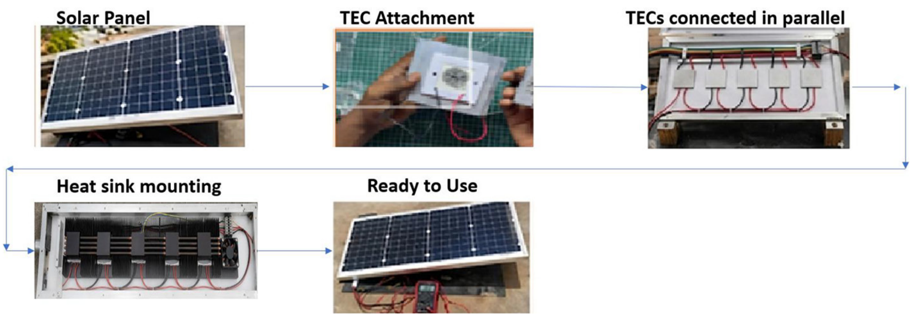


Figure 1. Assembly of the experimental setup

Figure 2. Experimental test setup

Table 4. Uncertainty analysis

Instrument	Parameter measured	Source of uncertainty	Type of evaluation	Error specification
Pyranometer	Solar irradiance G (W/m^2)	Calibration drift, temperature dependence, cosine response	Type B	
Digital multimeter	DC voltage (V)	Instrument resolution, internal resistance	Type B	±0.5%
Digital multimeter	DC current (A)	Shunt resistance heating, burden voltage	Type B	±1.0%
Temperature sensors	Surface/ module temperature (°C)	Probe positioning, contact resistance, cold junction compensation	Type B	±1.0%
Data acquisition system	Signal loading (V, I, T)	A/D conversion resolution, CJC error	Type B	±0.5%
Repeated tests	All parameters	Environmental fluctuations	Type A	

TEC hybrid experimental setups. This includes the pyranometer (for solar irradiance), a multimeter (for voltage and current measurements), and standard temperature sensors (Thermocouples/ RTDs) which are critical for capturing the maximum and minimum temperatures. The combined uncertainty of the solar-PV TEC system can be estimated using root squared method:

$$\frac{U_R}{R} = \sqrt{(\frac{\partial R}{\partial x_1}\frac{U_{x_1}}{R})^2 + (\frac{\partial R}{\partial x_2}\frac{U_{x_2}}{R})^2 + \cdots} \quad (6)$$

where: u_{x1}, u_{x2}, … are the measured parameters.

The propagated uncertainty in calculated HSEE was estimated to be ±3.2%, whereas the uncertainty in HSED was ±2.8%.

RESULTS AND DISCUSSION

Solar irradiation is measured during the April month of 2026 from 8:00 AM to 4:00 PM in the Rajam, India. And the average values of solar irradiation in W/m^2 are considered for analysis and is presented as a bar graph in Figure 3. This graph represents the hourly variation of the solar intensity during the day. At 8 AM, solar irradiation is less (400 W/m^2) and as the time passes it increases and it reaches a peak (900 W/m^2) at 1 PM. And then irradiation decreases significantly and at 4 PM irradiation drops to 350 W/m^2 as shown in Figure 3.

Figure 4 illustrates the variation of solar panel temperature (°C) with time over the course of the day for three configurations, solar PV with no TEC, with Bi_2Te_3, PbTe. The temperature of all solar panels increases from the morning 8 AM due to the increase in solar irradiance and reaches peak temperature at 1 PM and then gradually reduces towards the evening. It is identified that, solar PV system with no TEC consistently records higher temperature throughout the day due to accumulation of heat. But, the remaining two systems integrated with TEC modules exhibit lower

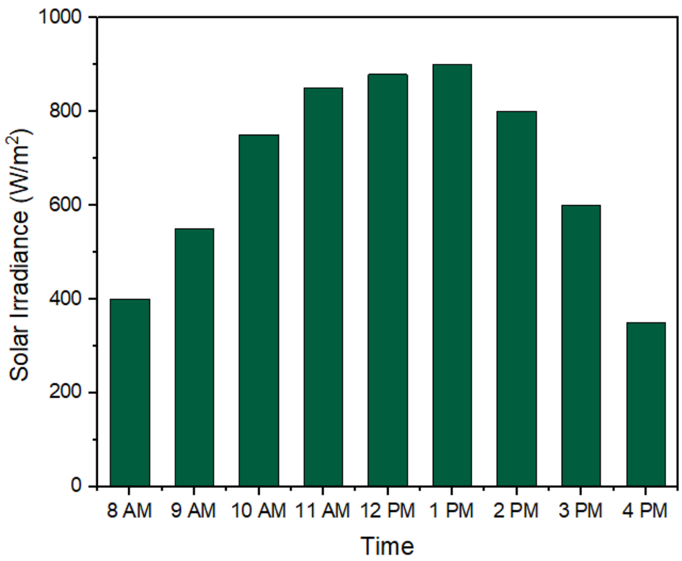


Figure 3. Solar irradiation (W/m^2) variation with time of intraday

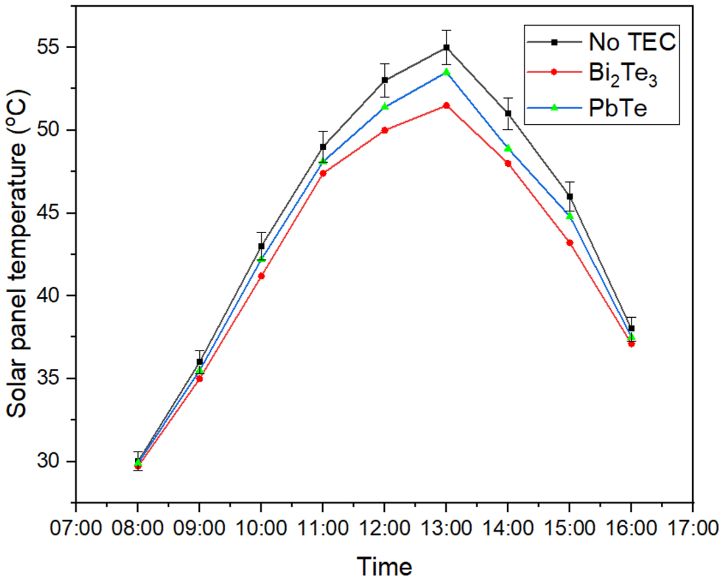
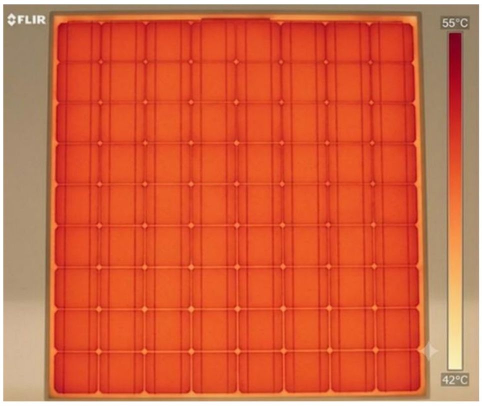
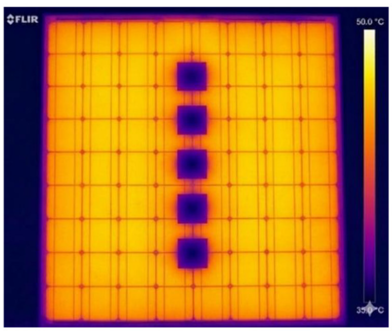


Figure 4. Solar panel temperature (°C) variation with time of intraday

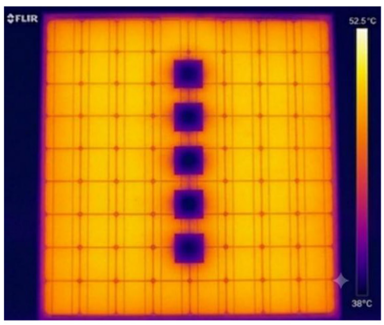
temperatures compared with no TEC which indicates active cooling. Among these two, Bi_2Te_3 based system exhibits lower temperature followed by PbTe based system. The maximum difference in panel temperature is observed at peak solar hours (1 PM). This shows the importance of thermal management system for solar PV system. The reduction in temperature of solar panel contributes to enhanced electrical and exergy efficiencies. Thermal images of solar panel when no TEC, Bi_2Te_3, PbTe cases are presented in Figure 5 and Figure 6 respectively. Figure 7 represents the variation of (a) voltage (b) current (c) power of solar PV panel with no TEC, Bi_2Te_3, PbTe TEC module



No TEC

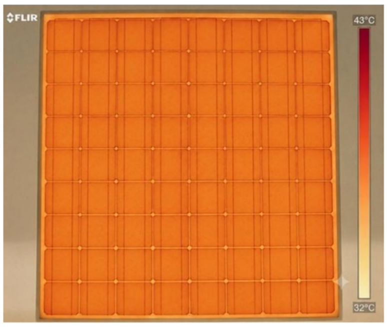


Thermal image (PV Panel with Bi_2Te_3)

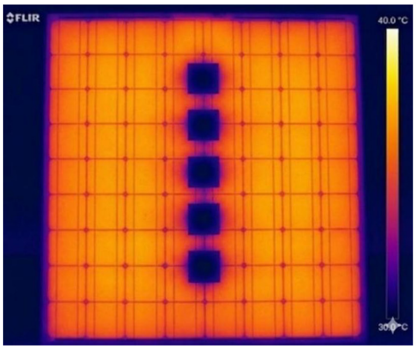


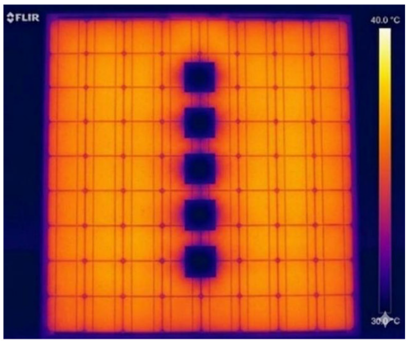
Thermal image (PV Panel with PbTe)

Figure 5. Thermal images of PV panel alone, PV with Bi_2Te_3, PV panel with PbTe during peak hour (1:00 PM)



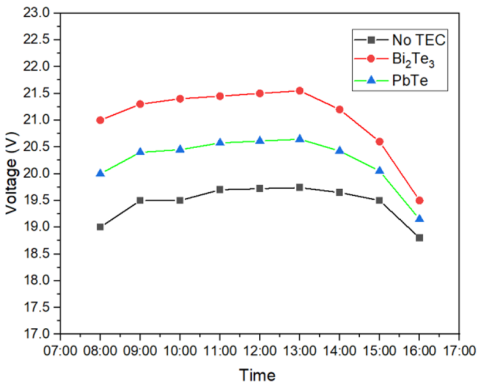
No TEC



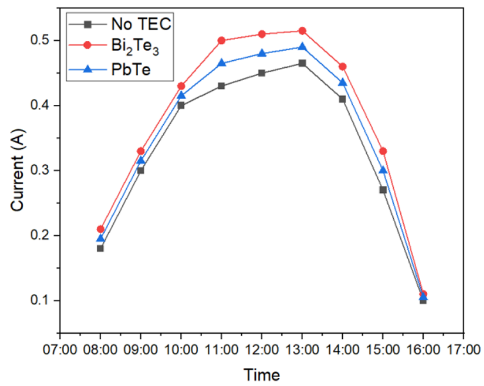


Thermal image (PV Panel with Bi_2Te_3) Thermal image (PV Panel with PbTe)

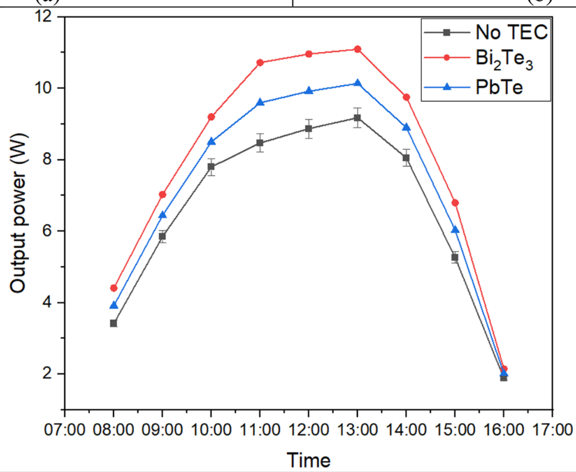
Figure 6. Thermal images of PV panel alone, PV with Bi_2Te_3, PV panel with PbTe during off peak hour (10:00 AM)



(a)



(b)



(c)

Figure 7. Solar panel: (a) coltage, (b) current, (c) output power variation with time of intraday

configurations. From Figure 7a, solar PV voltage slightly increases from morning hours till the midday hours and then starts declining towards evening. The TEC system with Bi_2Te_3 exhibits better voltage output across the day and followed by the PbTe system. From Figure 7b, a similar trend is observed but current increases gradually with time till 1 PM, and then decreases towards the evening as the solar irradiation starts decreased during the same period, The solar PV system integrated with TEC shows better current across the day due to its better thermal management. Among these two TEC materials, Bi_2Te_3 shows prominent results followed by PbTe. Figure 7c shows the variation of output power of solar PV panel which is influenced by voltage and current of the same. The power output increases significantly till the peak solar hours and TEC integration further enhances the output power. With Bi_2Te_3 system, maximum output power achieved is 10.59 ± 0.32 W followed by PbTe, as 9.63 ± 0.29 W.

Figure 8 represents the line graph shows the hourly variation of exergy input of solar PV system coupled with and without TEC. Exergy input is determined hourly from morning 8 AM to afternoon 4 PM. The exergy input peaks with reaching the maximum value of 88 W at 1 PM. This aligns with the peak solar irradiance as observed in Figure 3. A rapid increase in exergy input is observed from 8 AM to 11 AM where exergy doubles from 38 W to 77 W. After 1 PM, a sharp drop-off is observed to 33 W at 4 PM due to the fall in solar irradiation.

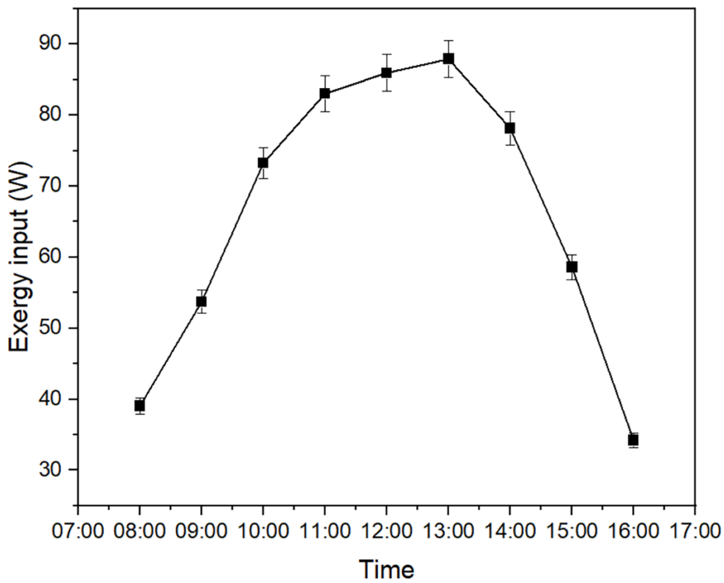


Figure 8. Solar exergy input variation with time

Table 5. Comparision of present study with previous literature on PV-TEC systems

Reference	Cooling/hybrid method	PV type/ application	Reported exergy efficiency	Major observation
Shittu et al. (2020)	PV-TEC with flat plate micro-channel heat pipe	PV module	12–14%	TEC integration reduced thermal losses and improved overall exergy performance
Singh et al. (2025)	PV-TEC air collector integrated solar dryer	Solar drying application	8.2%	Thermal energy storage improved drying and exergy characteristics
Sharifpur et al. (2022)	SWCNT/water nanofluid cooling	PV cooling system	15.98–16.00%	Nanofluid cooling enhanced thermal regulation and exergy efficiency
Alktranee and Péter (2023)	Evaporative cooling with aluminium fins	PV module	13%	Cooling reduced panel temperature and enhanced power output
Present study (Bi_2Te_3)	Hybrid PV-TEC based active cooling	Polycrystalline PV	12.04±0.37%	Bi_2Te_3 provided better thermal regulation and lower exergy destruction
Present study (PbTe)	Hybrid PV-TEC based active cooling	Polycrystalline PV	10.95±0.33%	PbTe showed moderate thermal management performance

Table 5 compares the present experimental results with previously reported PV cooling and hybrid thermoelectric studies. The reported literature values are based on different exergy accounting approaches. And several previous studies evaluated only PV-side exergy efficiency without explicitly subtracting TEC electrical consumption. The HSEE obtained in the present work using Bi_2Te_3-based thermoelectric cooling (12.04 ± 0.42%) is comparable with values reported in earlier PV–TEC investigations. Although nanofluid-assisted cooling methods reported slightly higher efficiencies, the present study demonstrates effective thermal regulation using compact thermoelectric cooling modules under real outdoor operating conditions. Furthermore, the comparative assessment between Bi_2Te_3 and PbTe under identical climatic conditions provides additional insight into material-dependent exergy behavior and thermal irreversibility reduction. Figure 9 represents the net power output with respect to time which is calculated from Equation 2.

Figure 10 represents the HSEE variation of three configurations, no TEC, Bi_2Te_3, PbTe with time during the day. It follows a typical diurnal trend increases from the morning, peaking around noon, and declining in the afternoon. Among them, Bi_2Te_3 based system exhibits highest HSEE of 12.04

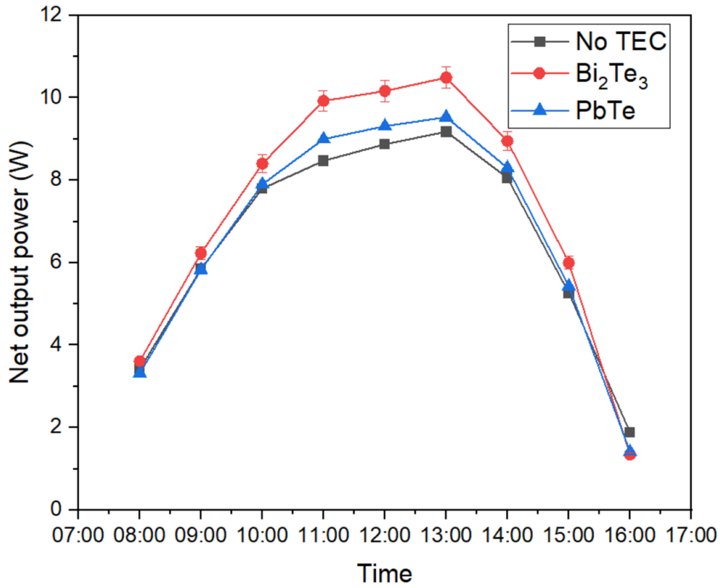


Figure 9. Net output power of PV-TEC hybrid system

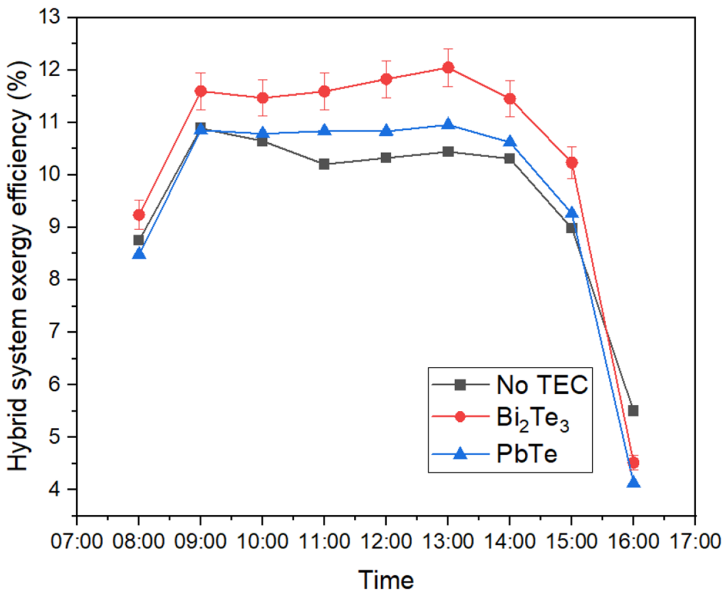


Figure 10. Hybrid system exergy efficiency variation with time

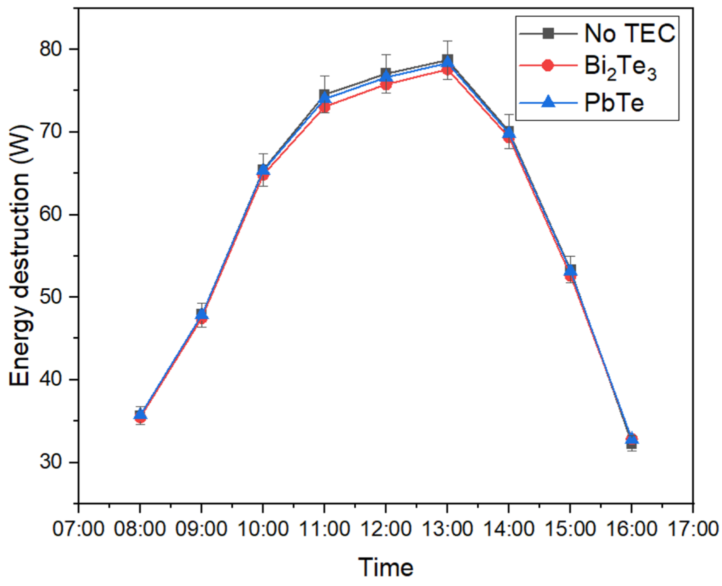


Figure 11. Variation of exergy destruction with time of day

± 0.37% followed by PbTe based system (10.95 ± 0.34%). And the solar PV system alone without TEC has exergy efficiency of 10.44 ± 0.32% only due to lacking of proper thermal management. In all the cases, a sharp decline is observed from the peak solar hours. It clearly shows the enhancement in the performance of solar PV system coupled with Bi_2Te_3 based TEC. Figure 11 shows the variation of HSED and time of day. HSED increases in the morning and reaches the peak during noon about 77.3 ± 2.18 W, and then decreases towards evening. The base line system has high exergy destruction indicating larger irreversibilities due to higher temperatures. On the other hand, Bi_2Te_3 based system with better thermal management has lower HSED (75.6 ± 2.04 W) and PbTe based system shows moderate HSED (76.6 ± 2.10 W).

CONCLUSIONS

The study investigated the exergy performance of solar PV system integrated with TEC (Bi_2Te_3 and PbTe as materials) and compared the system without TEC. Experimental results show that the Bi_2Te_3 system has lower peak panel temperature (51.4 ± 1.0 °C) followed by PbTe system got 53.2 ±1.0 °C and 55.6 ±1.0 °C for baseline system. The results indicate that the integration of TEC with solar PV system influences the thermal and energy behaviour as it serves as a good thermal manager. Among the two configurations, Bi_2Te_3 based system consistently showed better HSEE of 12.04 ± 0.37% and lower HSED of 75.6 W. On the other hand, PbTe system showed moderate HSEE of 10.95 ± 0.38% and baseline system showed only 10.44 ± 0.34%. So, Bi_2Te_3 based system has improved HSEE of 15.37% higher than no TEC system. In terms of irreversibilities, baseline system shows highest exergy destruction of 77.3 W and PbTe lying in between. The diurnal analysis stated that both HSEE and HSED follow the trend of solar irradiance peaking at 1 PM and decreasing towards evening. The results indicate that TEC integration improves PV thermal regulation and electrical behavior under the tested operating conditions. Bi_2Te_3 performs as the more effective TEC material compared to PbTe in terms of exergy input and HSEE. This study may support the design of thermally regulated PV systems. Results indicate that Bi_2Te_3 provides better thermal regulation compared with PbTe under the tested operating conditions. However, when TEC electrical consumption is included, the net thermodynamic benefit depends on the balance between enhanced PV output and cooling power demand. Therefore, hybrid-system exergy analysis is essential for realistic performance assessment. The proposed approach may contribute to improved utilization of solar energy systems and may support the development of thermally regulated PV systems for improved operational performance.

Acknowledgements

Authors of this article are grateful for the management of GMRIT deemed to be university for facilitating required infrastructure for completing this work.

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