

Simulation-Based Performance Assessment of Hybrid Photovoltaic–Thermoelectric Systems

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Abstract. Hybrid photovoltaic–thermoelectric (PV–TE) systems provide an effective approach to enhance solar energy utilization by combining electrical power generation with waste heat recovery. Conventional photovoltaic (PV) modules suffer from efficiency degradation at elevated operating temperatures, especially under high solar irradiance. Integrating thermoelectric generators (TEGs) with PV modules enables partial conversion of excess heat into additional electrical power while reducing PV operating temperature. This study investigates a hybrid PV–TE system employing passive cooling using aluminium fin heat sinks. A coupled thermal–electrical model is developed under steady-state conditions, in which the PV module power is fixed at 70 W and the cold-side temperature of the TEG is maintained at 27 °C, while the hot-side temperature is varied to evaluate the thermoelectric contribution. The results reveal a strong dependence of power improvement on the temperature difference across the TEG. Specifically, the power improvement increases from approximately 0.95% at 50 °C to 1.36% and 1.75% at 60 °C and 70 °C, respectively, and reaches about 2.87% at 100 °C.

1 Introduction

Accelerating global energy demand and growing concern over greenhouse gas emissions have stimulated research into renewable technologies [1]. Photovoltaic (PV) systems have become one of the most mature and widely deployed renewable technologies because they convert sunlight directly into electricity with no moving parts [2]. Despite their success, PV cells only convert a small portion of the solar spectrum into electricity; about 80 % of the absorbed energy is dissipated as heat [2]. The accumulation of heat in the cell raises its temperature and reduces conversion efficiency by roughly 0.25 - 0.5 % as the temperature increases by 1°C, depending on the cell type [3]. Increasing incident flux using reflectors or concentrators can boost power output but further elevates cell temperature and exacerbates efficiency losses [4].

Conventional crystalline silicon PV cells consist of a thin p-n junction fabricated from semiconductor material sandwiched between a transparent cover and encapsulant layers with a protective back sheet [3]. Cell temperature has a strong influence on PV performance.

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Research showed that the efficiency of polycrystalline modules decreases by about 0.469 % as the temperature increases by 1°C [4], while crystalline silicon modules generally lose 0.4–0.5 % and amorphous silicon modules around 0.05 % [6]. High solar irradiation increases electrical power but also raises cell temperature, leading to a trade-off between power and efficiency [4]. Using reflectors or concentrators can significantly increase output power, yet higher reflector angles or heights raise module temperature and reduce efficiency [7].

Thermoelectric generators (TEGs), which convert temperature differences directly into electrical power via the Seebeck effect, offer a solid state means of harvesting some of this waste heat [5]. Hybrid PV–TEG systems aim to recover a portion of the thermal losses from PV modules and convert them to electricity, thereby modestly increasing overall system performance. TEGs generate power by exploiting the Seebeck effect: a voltage is produced when there is a temperature difference across a junction of n-type and p-type semiconductors [5]. They have no moving parts, are silent and exhibit long service life, making them attractive for waste heat recovery [8]. The performance of a thermoelectric material at a given temperature T is characterized by the dimensionless figure of merit (ZT), which determines the maximum achievable thermoelectric conversion efficiency. It is defined as:

$$ZT = \frac{S^2 \sigma}{\kappa} T \quad (1)$$

where S is the Seebeck coefficient, σ the electrical conductivity, κ the total thermal conductivity and T the absolute temperature [9]. High ZT requires a large power factor $S^2\sigma$ and low thermal conductivity. Classic bismuth telluride (Bi_2Te_3) systems achieve $ZT \approx 1$ near room temperature, while modern materials such as tin selenide (SnSe) and tin sulfide (SnS) heterostructures exhibit strong phonon anharmonicity and ultra low lattice thermal conductivity, leading to ZT values above 2.5 [10]. The theoretical analysis of thermoelectric efficiency is analogous to the thermodynamic treatment of PV efficiency; the Shockley–Queisser limit review notes that minimizing entropy generation is central to approaching ideal conversion [11].

Commercial hybrid PV–TEG systems commonly use Bi_2Te_3 because it offers the best room temperature performance and is readily available. Research continues to explore higher performance materials, including lead chalcogenides, skutterudites, half-Heusler compounds and layered IV–VI semiconductors. Polycrystalline SnSe with removal of tin oxide impurities has achieved $ZT \approx 3.1$ at 783 K [10], and a recent study predicted that SnSe/SnS superlattices undergo a phase transition to a $P4/nmm$ structure with extremely low lattice thermal conductivity and promising electronic properties, suggesting potential for both photovoltaic and thermoelectric applications [10]. Beyond materials, the geometry of a TEG module significantly affects performance. Finite element modelling shows that the maximum power occurs when the cross-sectional area of the n-type leg equals that of the p-type leg, and that contact resistance must be minimized to avoid power losses [8]. Simulation-guided design using simulation tools explores alternative geometries (e.g., annular or uni-leg structures) to reduce thermal stresses and improve reliability [9].

Hybrid PV–TEG systems attach TE modules to the backside of PV panels so that a portion of the waste heat flows through the TEG. A heat spreader (often a copper plate) distributes heat across the TE modules, and a heat sink on the cold side dissipates heat to maintain a temperature difference. Hashim and coworkers developed a theoretical model describing energy flows in such systems; absorbed solar energy is balanced by convective, radiative and conductive losses plus the electrical power output [12]. The net electrical power is the sum of the PV and TE contributions:

$$P_{PV-TEG} = P_{PV} + P_{TEG} \quad (2)$$

Similarly, the overall conversion efficiency of the hybrid system is represented as the combined efficiency of the PV and TEG subsystems:

$$\eta_{PV-TEG} = \eta_{PV} + \eta_{TEG} \quad (3)$$

Because PV efficiency decreases with temperature while TE output increases with temperature difference, there is an inherent trade off that must be optimized [3]. Detailed balance analysis indicates that the ultimate efficiency gains from adding a TEG to a single junction PV cell is modest—around 5 % under one sun illumination and up to 15 % under concentrated sunlight [2]. Several experiments have validated hybrid PV–TEG concepts. Khan and colleagues attached ten B_2Te_3 modules to a 10 W polycrystalline PV panel and reported that the hybrid system reduced the PV operating temperature by about 3 °C and increased total power output by 19 %, raising efficiency from 11.6 % to 14 % [13]. A subsequent study modelled PV–TEG systems under non tracking and solar tracking conditions and concluded that the optimum number of TEG modules was approximately 336 for fixed systems, with slightly higher numbers for single and dual axis tracking [5]. Empirical studies on hybrid designs combining TEGs with heat sinks show that coupling a TE module to an aluminum fin heat sink can cool the PV cell by roughly 8 °C and improve cooling performance by 27 % in addition to generating electrical power [14].

Efficient thermal management is crucial for maintaining PV efficiency and providing adequate temperature difference for the TEG. Passive techniques include natural convection fins and heat sinks, while active methods employ water sprinkling, forced air and pumped liquid cooling. Nasrin et al. demonstrated that attaching a heat exchanger and circulating water or air can keep cell temperature low and improve PV efficiency [4]. Khan et al. compared various cooling techniques combined with aluminum foil reflectors; water sprinkling, passive heat sinks, air fans and closed loop cooling increased output power by 22.75 - 38.55% [6].

This study aims to design a hybrid PV–TEG system using simulation tools and to evaluate its performance based on the properties of Bi_2Te_3 thermoelectric material. The material data are incorporated into the model to analyze the system efficiency under specified operating conditions. The simulation framework is used to investigate the interaction between thermal and electrical behaviors, providing insight into the overall performance of the proposed system.

2 Methodology

Bismuth telluride (Bi_2Te_3) was selected as the thermoelectric material in this study due to its well-established performance in low- to medium-temperature applications, which matches the typical operating temperature range of photovoltaic (PV) modules. Bi_2Te_3 exhibits a relatively high dimensionless figure of merit ($ZT \approx 1$ at room temperature). Moreover, Bi_2Te_3 -based TEGs are commercially available, stable, and widely reported in hybrid PV–TEG literature, making them a suitable and practical choice for both experimental validation and numerical simulation. These characteristics allow Bi_2Te_3 to effectively convert waste heat from the rear surface of PV modules into additional electrical power while simultaneously contributing to thermal regulation of the PV system. The numerical model of the hybrid PV–TEG system was developed using material properties of Bi_2Te_3 obtained from the literature. Key thermoelectric parameters, including thermal conductivity, Seebeck coefficient, and

electrical resistivity, were adopted as inputs for the simulation model. The values of these material properties were extracted from the literature. [15]. These parameters were assumed to be temperature-dependent within the operating range of the system to ensure realistic simulation behaviour. By incorporating accurate thermophysical and thermoelectric properties, the model aims to reliably predict the electrical output and power improvement achievable from the integration of a Bi_2Te_3 -based TEG.

3 Results and Discussion

In this study, the PV module power was fixed at a rated capacity of 70 W to establish a consistent baseline for performance comparison. The operating temperature of the TEG was varied while maintaining the PV electrical characteristics unchanged. The simulation was conducted by systematically varying the hot-side temperature of the Bi_2Te_3 -based TEG, specifically designed for this study with 126 n-p couples, to evaluate its influence on the total electrical power output of the hybrid PV-TEG system, as shown in Fig. 1. The resulting power improvement was calculated by comparing the combined PV-TEG output with the standalone PV output under identical conditions. This approach allows the direct assessment of the contribution of thermoelectric energy harvesting as a function of temperature difference, providing insight into the thermal operating range in which the hybrid PV-TEG system offers the most significant performance enhancement.

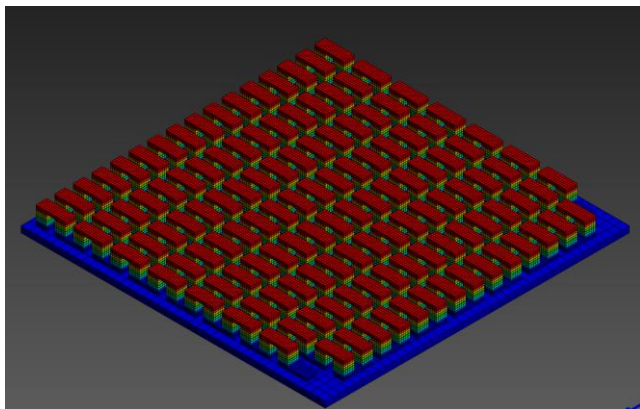


Figure 1. Simulated model of the Bi_2Te_3 -based thermoelectric generator (TEG) array, designed and developed in this study for integration into the hybrid PV-TEG system. The color gradient from red to blue represents the temperature distribution, where red indicates the hot side and blue represents the cold side of the TEG.

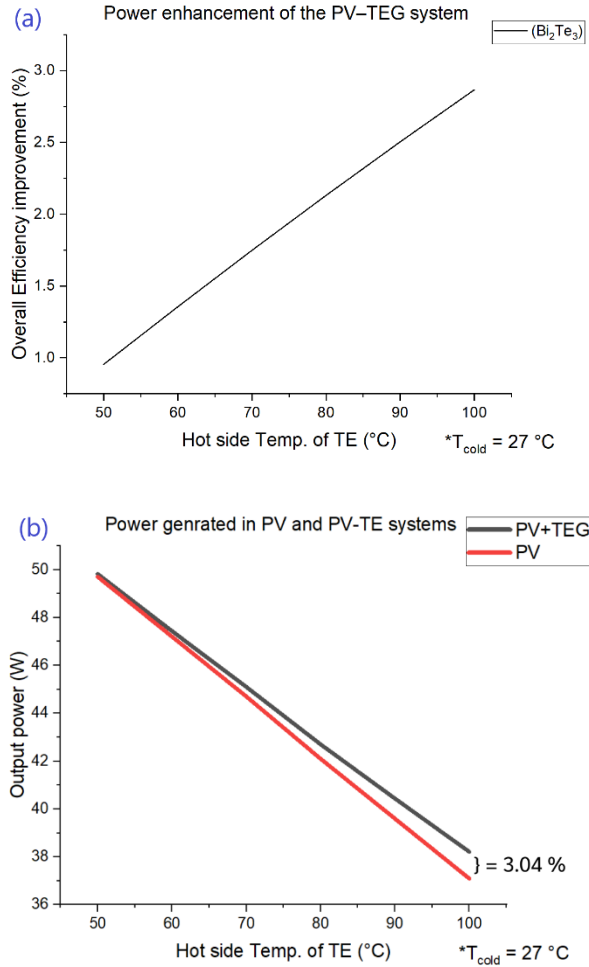


Figure 2. (a) Power enhancement of the hybrid PV–TEG system as a function of the hot-side temperature of the thermoelectric generator using Bi₂Te₃, with the cold-side temperature maintained at 27 °C. The efficiency improvement increases with increasing temperature difference across the TEG. (b) Output power comparison between the standalone PV system and the hybrid PV–TEG system under varying hot-side temperatures. The hybrid system consistently generates higher power, with a maximum improvement of approximately 3.04% at 100 °C.

Figure 2. (a) shows the simulated power improvement of the hybrid PV–TEG system as a function of the TEG hot-side temperature, while maintaining the PV module power at 70 W and the TEG cold side at 27 °C. The results clearly indicate that the overall power output increases with the temperature difference across the TEG. At a hot-side temperature of 50 °C, the power improvement is only about 0.95%, but it gradually rises to 1.36% and 1.75% at 60 °C and 70 °C, respectively. The highest improvement of 2.87% occurs at 100 °C, demonstrating that a larger thermal gradient significantly enhances the thermoelectric contribution to the hybrid PV–TEG system’s total power output. **Figure 2.** (b) illustrates the output power of the standalone PV system and the hybrid PV–TEG system as a function of the hot-side temperature of the thermoelectric generator, with the cold-side temperature maintained at 27 °C. As the hot-side temperature increases from 50 °C to 100 °C, the output power of both systems decreases due to the thermal degradation of PV performance. However,

the hybrid PV–TEG system consistently produces higher power than the standalone PV system across all temperature conditions.

The results show that the integration of the TEG provides an additional power contribution, which becomes more significant at higher temperatures. At 100 °C, the hybrid system achieves an improvement of approximately 3.04% compared to the PV-only system. This trend highlights the effectiveness of utilizing waste heat through the TEG to partially compensate for the loss in PV efficiency at elevated temperatures.

In this work, the proposed PV–TEG system is designed and simulated using Bi₂Te₃ material properties under a single operating condition as a baseline case. This study serves as a preliminary investigation for future development. In subsequent work, the research will be extended to include other thermoelectric materials, such as SnSe and PbTe, as well as different Bi₂Te₃ operating conditions. Additionally, geometric parameters and dimensions of the system may be further optimized to enable a comprehensive performance comparison.

4 Summary

Overall, the results demonstrate that the performance of the hybrid PV–TEG system is strongly influenced by the temperature difference between the hot and cold sides of the thermoelectric generator. With the cold side maintained at 27 °C, increasing the hot-side temperature produces a nonlinear rise in total power output. These findings confirm that the proposed PV–TEG system can be effectively designed and utilized as a foundation for further development and optimization of hybrid energy systems.

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