

A Review on Optimization of PV-TEG Hybrid Model

Pallavi Roy¹, Aditya Roy², Bani Kanta Talukdar³

¹Department of Electrical Engineering, Girijananda Chowdhury University
Azara, Hathkhowapara, Guwahati-781017, Assam, INDIA.
¹pallavi_ee@gimt-guwahati.ac.in*

²Department of Electrical Engineering, Girijananda Chowdhury Institute of Management and Technology,
Azara, Hathkhowapara, Guwahati-781017, Assam, INDIA.
²adityaroy260603@gmail.com

³Department of Electrical Engineering, Assam Engineering College
Jalukbari, Guwahati-781014, Assam, INDIA
³bktalukdar.ele@aec.ac.in

Abstract: *The integration of photovoltaic (PV) panels and thermoelectric generators (TEGs) in a hybrid energy system is a promising development in renewable energy technology. The hybrid system is based on combining the strengths of both PV and TEG technologies to maximize energy production and efficiency. While PV panels are efficient in converting sunlight into electricity, their performance often suffers due to heat losses, especially at high temperatures. The use of TEGs addresses this challenge through the capture of waste heat produced by the PV panels and its conversion into further electrical energy by the Seebeck effect, thereby increasing the overall energy output. In this review, a systematic literature analysis has been conducted through various case studies, and simulation-based research relevant to PV-TEG hybrid systems. These were assessed based on performance metrics, design configurations, material innovations, and thermal management techniques. The review methodology includes a structured analysis of experimental studies, and numerical simulations. Sources have been selected based on relevance to system performance, material properties, and design innovations. This analysis highlights that PV-TEG hybrid systems can enhance overall energy conversion efficiency by 10–20% in optimized configurations. It is seen that power output improved with bismuth telluride-based modules, enhanced cooling using heat sinks and phase change materials, and better power tracking using intelligent MPPT algorithms. Thus, it is crucial to pay more attention to thermal management, material selection, and system design in order to optimize PV-TEG hybrid systems. Proper thermal management enhances TEG performance, and there are efficiency gains concerning the PV panels under all environments. Advanced heat sink design with high-performance thermal interface materials can significantly enhance both energy conversion efficiency and heat dissipation. It is observed that PV-TEG systems can reduce reliance on conventional energy sources, offering more sustainable and efficient alternatives to power generation. Challenges with material compatibility, cost, and scalability remain major barriers to the practical implementation of these systems, and continued research into finding cost-effective materials and innovative system designs will be necessary. In future studies, the focus should be put on the discovery of new thermoelectric materials and scaling up the techniques involved in system integration. PV-TEG hybrid systems would then be a far better choice for the world's global energy crisis.*

Keywords: Energy conversion efficiency; Heat dissipation; MPPT algorithms; Phase change materials; Photovoltaic (PV) panels; Seebeck effect; Thermoelectric generator (TEG)

Open Access. Copyright ©Author(s). Distributed under [Creative Commons Attribution 4.0 International License \(CC-BY\)](https://creativecommons.org/licenses/by/4.0/).
Article history- Received: 4 February 2025 and Accepted: 16 May 2025.

1. Introduction

The increasing demand for sustainable energy solutions has driven the development of renewable energy technologies to reduce environmental impact and reliance on depleting fossil fuels [1]. Among

renewable sources, solar energy stands out due to its widespread availability and its ability to generate electricity directly from sunlight [2]. The construction and design of solar PV (photovoltaic) systems have steadily gained attention as an effective energy resource. It has to be kept in mind,

though, that part of their efficiency is considerably dampened by thermal losses such as overheating, which reduces efficiency and energy production [3]. TEGs (thermoelectric generators) act as a supplement for PV systems because they work on the basics of the Seebeck effect, which converts a temperature differential into electrical energy [4]. TEGs help convert waste heat produced from PV panels back into the energy cycle, hence improving the overall energy output of solar systems. This integration produces a combined TEG and PV system, which is referred to as a PV-TEG hybrid [5]. This concentrated or dual approach increases the range of resources used and in turn, improves the efficiency of the systems themselves. Hybrid PV and TEG systems have the potential to generate a lot of power but are still at their younger stages of development, and thus many issues or obstacles still stand in their path [6]. Novel and effective thermal management, material selection, and inexpensive and efficient design are key factors that must be addressed in order to maximize their effectiveness. Hybrid PV-TEG systems have demonstrated the potential to significantly enhance energy output by efficiently utilizing waste heat generated by PV panels. This integration not only addresses the thermal inefficiencies of PV systems but also opens pathways for improved device structures and material innovations to optimize performance. However, challenges such as ensuring material compatibility, reducing fabrication complexity, and achieving cost efficiency remain critical hurdles that need to be overcome for the widespread adoption and scalability of this promising technology [7].

2. Theoretical Background of PV-TEG Hybrid Systems

A photovoltaic system, often referred to as a PV system, is a method for generating electrical power by converting solar energy into electricity using semiconducting materials that exhibit the photovoltaic effect. These systems are environmentally friendly, generate low carbon emissions, and are a key technology in advancing renewable energy solutions globally. As illustrated in Figure 1, the fundamental component of PV systems is the p-n junction solar cell. When sunlight strikes the solar cell, photons are absorbed, generating electron-hole pairs within the semiconductor material. The p-n junction directs the movement of these electrons toward the front contact, creating an electric current. While this process is efficient, the performance of PV systems is often limited by thermal losses, as excess heat reduces their efficiency. To address this challenge, hybrid systems integrating complementary technologies, such as thermoelectric generators, have been explored to enhance overall energy conversion efficiency. Thermoelectric generators

(TEGs) utilize the Seebeck effect to directly convert waste heat into electrical energy, thus offering a sustainable and environmentally friendly energy recovery solution. Their solid-state design, quiet operation, and adaptability make them suitable for diverse applications, although challenges such as low conversion efficiency remain. Recent advancements in materials and system designs continue to enhance their performance and potential for widespread use. The photovoltaic-thermoelectric generator (PV-TEG) systems hyphenate solar electricity production and heat recovery. With a TEG, one generates additional power from otherwise lost heat through the Seebeck effect. This way is more energy-efficient, yet how much depends on how effective TEG is and, in turn, how much that increases by its effects of temperature on PVs. This may even be partially detrimental at times because of heat-caused degradation of PV outputs.

2.1 Photovoltaic (PV) Systems

Photovoltaic systems are widely used to convert solar energy into electricity through the photovoltaic effect. The photovoltaic effect occurs when sunlight hits a PV cell, which is usually made of semiconductor materials such as silicon, and excites electrons to produce an electric current which is shown in Figure 1. In PV-TEG systems, the Seebeck Effect enables the direct conversion of waste heat into electricity. When a temperature gradient (ΔT) is established across a thermoelectric material, a voltage (V) is induced, given by $V = S \cdot \Delta T$, where S is the Seebeck coefficient. This effect enhances overall energy efficiency by utilizing excess heat, though its effectiveness depends on material properties, thermal management, and system integration [8]. However, the efficiency of PV systems is limited by thermal losses. Excess heat produced during operation degrades the performance of the system and eventually causes material degradation [9]. The performance of PV panels is characterized by current-voltage (I - V) and power-voltage (P - V) curves, which are sensitive to environmental factors such as irradiance and temperature. As an example, an increase in temperature reduces the open-circuit voltage (V_{oc}) of the PV panel, reducing its efficiency [10]. This inherent inefficiency calls for supplementary technologies to capture and utilize the waste heat produced during operation.

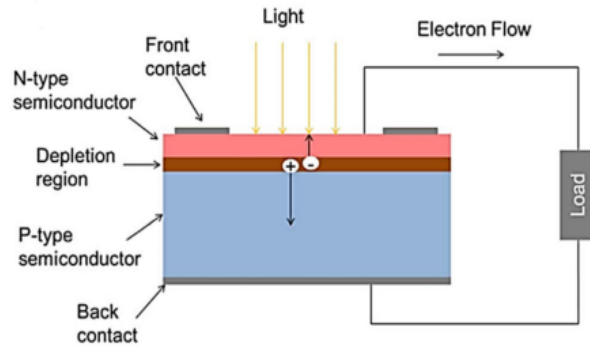


Figure 1: A p-n junction solar cell [15]

2.2 Thermoelectric Generators (TEGs)

TEGs provide a practical approach toward the use of waste heat by converting temperature differences to electrical energy using the Seebeck effect. When a temperature gradient is present in a thermoelectric material, an electrical voltage proportional to the gradient is developed [11]. Figure 2 illustrates this principle, where the key components of a TEG system, including thermoelectric elements sandwiched between a heat source and a heat sink. Heat flows from the hot side to the cold side, driving the movement of charge carriers within the thermoelectric material and producing electrical power. TEGs are solid-state devices with no moving parts; they are thus reliable and useful in hybrid energy systems [12]. The efficiency of TEGs is controlled by the temperature gradient, ΔT , and the thermoelectric material's properties, described by its **dimensionless figure of merit, ZT** [13]. Materials like bismuth telluride are widely used due to their high thermoelectric efficiency [14]. Although TEGs are less efficient than PV systems for direct energy conversion, they excel in capturing and converting waste heat, making them suitable for hybrid configurations.

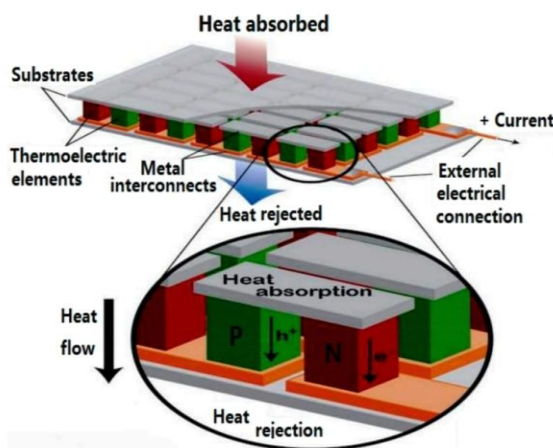


Figure 2: Schematic of the Seebeck effect in a thermoelectric generator [5]

In practical TEG modules, the Seebeck effect generates a voltage proportional to the temperature difference (ΔT) between the hot and cold sides, making the maintenance of a large ΔT essential for maximizing power output and conversion efficiency. The intrinsic efficiency of a thermoelectric material is defined by its dimensionless figure of merit, ZT , which depends on a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity. Materials with higher ZT values offer better energy conversion, but most commercially available thermoelectric materials, such as bismuth telluride, still have ZT values close to 1, limiting practical efficiency. In hybrid PV-TEG systems, maintaining a sufficient ΔT is particularly challenging, as the cold side is often constrained by ambient environmental conditions. In warmer climates or low airflow situations, the ambient temperature approaches that of the PV panel, thereby reducing the temperature gradient and drastically lowering TEG output. This problem is compounded by the low ZT of current materials, meaning that even moderate ΔT values do not translate into significant electrical generation. Effective thermal management, such as using heat sinks, heat pipes, or phase change materials is crucial to maintaining this temperature gradient. Without it, the thermoelectric contribution remains minimal. Therefore, both the development of high- ZT thermoelectric materials and the implementation of advanced cooling strategies are necessary to unlock the full potential of PV-TEG hybrid systems.

2.3 PV-TEG Hybrid

System Overview It enables both to make use of solar radiation as well as waste heat concurrently by the hybrid system for integration, thus improving energy efficiency overall [15]. In such an arrangement, the photovoltaic panel generates electricity by making use of sun radiations, and on the other hand, TEG harnesses the waste heat emitted by the photovoltaic panel [16]. This helps eliminate thermal inefficiencies existing with photovoltaic alone, while total energy output improves in value. The PV-TEG hybrid systems offer the possibility of dual-energy utilization through the generation of electricity from both sunlight and waste heat. Recovery of waste heat enhances the overall efficiency of energy conversion, thus making the systems suitable for applications ranging from small portable devices to large solar farms [17]. However, challenges in terms of thermal management, material compatibility, electrical integration, and cost-effectiveness must be addressed to optimize performance and scalability [18].

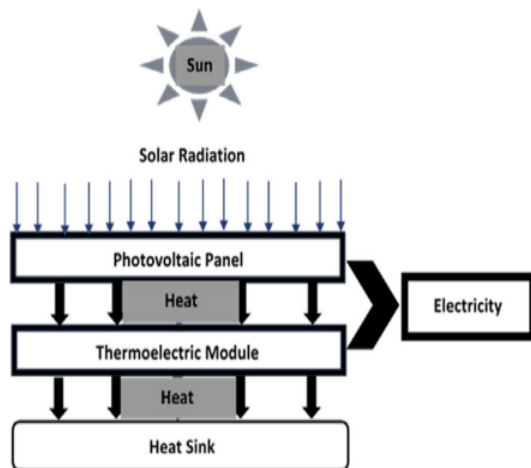


Figure 3: Schematic of an integrated PV-TEG system [15]

Figure 3 depicts the schematic of an integrated PV-TEG system. In this setup, the photovoltaic panel captures solar radiation to generate electricity, while the thermoelectric module positioned beneath it utilizes the waste heat from the panel to produce additional power. A heat sink is placed below the thermoelectric module to dissipate excess heat efficiently, ensuring optimal performance and preventing thermal degradation. This dual-energy harvesting design improves the overall efficiency of the system by making effective use of both solar energy and the associated thermal energy.

2.3.1 Current Trends in PV-TEG Structures

As it has been mentioned previously, a hybrid system incorporating Photovoltaic (PV) and thermoelectric modules enhances the performance of energy harvesting. One of the most popular approaches is a layered configuration, with TEG still below PV but slightly tilted to mitigate the effects of shadows upon it. This approach guarantees satisfactory thermal coupling between the PV and TEG although a mismatch in thermal management will lower the efficiency of thermoelectric conversion [19].

On the other hand, parallel arrangements enable the use of structural modules which employ a configuration in which both solar photovoltaic and TEG modules are positioned to face the sun in addition to concentrating solar radiation on the solar photovoltaic panels. While this will minimize the thermal interaction between solar photovoltaic and TEG modules, it adds more complexity to the overall system because of the provision of heating [20]. In recent works, TEGs were integrated within layered PVs. Such integrated design reduces both

space and increases the amount of heat that can be utilized within the design. However, these systems usually have degraded electrical and thermal performance for large applications [21].

2.3.2 Innovations in Material and System Architecture

Recent developments in thermoelectric materials have considerably increased the viability of systems hybridization with PV-TEG modules. Nanostructure thermoelectric materials, including bismuth telluride, are expected to have better thermoelectric and electrical characteristics [22]. These composites are low thermal conductors, yet of high electrical conductance which increases the thermoelectric figure of merit (ZT). Also, light and flexible thermoelectric materials have been manufactured for better integration with photovoltaic panels thus increasing the versatility of hybrid systems [23].

Concerning system configuration, bulk transmission and heat sink technologies have been enhanced to exhaust the heat away from TEG modules and yet not disturb the temperature differentials below optimal levels. Heat pipe cooling and liquid thermal control have been instrumental in ensuring the optimal performance of hybrid systems in different environmental conditions [24]. Moreover, newly introduced configurations of the PV panels, such as bifacial solar cells and anti-reflective coating, have assisted in minimizing heat loss and increasing the efficiency, hence increasing the suitability of hybrid systems integration [25].

2.3.3 Improvement Tactics for Hybrid Energy System

The design and optimization of PV-TEG hybrid systems begins with understanding their functional and operational requirements and limitations in a bid to maximize energy conversion. For this, thermal considerations are of high significance, accompanied by the development of effective thermal insulation systems and the layout of TEG modules that promote the required heat flow without reducing the efficacy of the PV. Electrical integration is of high relevance as well, as some researchers in this field, concentrate on the design of specialized power electronics and MPPT algorithms for hybrid PV-TEG systems. These objectives are intended to dovetail the outputs of the PV and TEG modules so that the energy losses are cut down and the operation of the system is as close to perfect as it can get [26].

Another important factor has been the tools of modeling and simulation. Hybrid systems have been examined in the MATLAB and COMSOL environments to test their performance under

various external operating conditions and find the best configuration that fits their intended use. The effectiveness and the possibility of mass production also come to the fore, especially when considering large-scale deployment such as solar farms where cost and performance need to strike a balance [27].

Table 1: Glossary of Key Terms and Parameters

Symbol	Definition
ZT	Dimensionless figure of merit for thermoelectric materials: $ZT = \frac{S^2 \sigma T}{k}$, where S is the Seebeck coefficient, σ is electrical conductivity, T is temperature, and k is thermal conductivity.
ΔT	Temperature difference between the hot and cold sides of the TEG.
AOA	Arithmetic Optimization Algorithm: A metaheuristic technique used for Maximum Power Point Tracking (MPPT) in PV-TEG systems.
CFD	Computational Fluid Dynamics: Simulation method used for analyzing heat transfer and fluid flow in PV-TEG systems.
Seebeck Coefficient (S)	Voltage generated per unit temperature difference in a thermoelectric material ($\mu V/K$).
Efficiency (η)	Ratio of electrical output to input solar energy. In hybrids, includes both PV and TEG contributions.

3. Mathematical Formulation for the Optimization of PV-TEG Hybrid Model

The comprehensive mathematical framework required for the analysis and optimization of the PV-TEG hybrid system would enable it to quantify energy interactions such as absorption of solar energy, losses, and power generation from electricity. All contributions of the PV modules and TEG modules will be systematically accounted for as a foundation for understanding processes of energy conservation and conversion. The equations in this section are developed to quantify the efficiency and the performance of the hybrid system, thus providing crucial insight for optimizing the design.

3.1 Energy Conservation in the Hybrid System

The equation (1) represents the fundamental energy balance of the hybrid system, where all incoming solar energy is either converted into electrical power or dissipated as heat [6, 28].

$$E_{\text{sun}} = E_{\text{loss}} + P_{\text{el}} \quad \dots (1)$$

where:

- E_{sun} : Total solar energy incident on the system (W).
- E_{loss} : Energy lost through radiative, convective, and conductive heat transfer (W).
- P_{el} : Total electrical power output of the system, including contributions from the PV and TEG modules (W).

This relationship ensures that all incoming solar energy is either converted into electrical power or dissipated as heat, forming the foundation for analyzing energy flow within the hybrid system.

3.2 Solar Energy Absorption by the PV Module

The equation (2) quantifies the solar energy absorbed by the PV module, based on radiative heat transfer and optical properties of the system, [10], [29].

$$E_{\text{sun}} = G \cdot A_{\text{PV}} \cdot \tau_g \cdot \alpha_{\text{cell}} \quad \dots (2)$$

where:

- G : Solar irradiance (W/m^2), representing the intensity of sunlight incident on the module.
- A_{PV} : Surface area of the PV module (m^2).
- τ_g : Transmissivity of the protective glass, accounting for the fraction of sunlight passing through.
- α_{cell} : Absorptivity of the PV cells, indicating their efficiency in capturing solar radiation.

The equation (2) highlights the influence of material properties (τ_g , α_{cell}) and the PV module's design in determining the amount of energy available for conversion.

3.3 Electrical Output of the PV Module

The equation (3) calculates the PV module's electrical output under real operating conditions by accounting for temperature effects on efficiency, [10], [33].

$$P_{el,PV} = \eta_o \cdot [1 - \beta \cdot (T_{cell} - T_{ref})] \cdot \tau_g \cdot G \cdot A_{PV} \quad \dots (3)$$

where:

- η_o : Standard efficiency of the PV module at reference conditions (25°C or 298.15 K).
- β : Temperature coefficient (1/°C), denoting the efficiency drop per degree rise above the reference temperature.
- T_{cell} : Operating temperature of the PV cells (K).
- T_{ref} : Reference temperature (K).
- τ_g, G, A_{PV} : As defined already in eqn. (2).

This formulation underscores the importance of maintaining optimal cell temperature to mitigate efficiency losses, as described by the $\beta \cdot (T_{cell} - T_{ref})$ term.

3.4 Thermoelectric Generator (TEG) Power Output

The equation (4) defines the TEG module's electrical output as a product of its thermal input and conversion efficiency, [13], [14].

$$P_{el,TEG} = \eta_{TEG} \cdot Q_{TEG} \quad \dots (4)$$

where:

- η_{TEG} : Efficiency of the TEG module, influenced by material properties and the temperature gradient.
- Q_{TEG} : Heat transferred through the TEG module (W).

The performance of the TEG depends on maximizing Q_{TEG} and selecting materials with high thermoelectric efficiency.

3.5 Heat Transfer through the TEG Module

The equation (5) quantifies the heat flow across the thermoelectric material, derived from Fourier's law as applied to thermoelectric modules [13, 31].

$$Q_{TEG} = \frac{M \cdot K_{TEG} \cdot A_{TE} \cdot N}{L_{TE}} \cdot (T_H - T_C) \quad \dots (5)$$

where:

- M : Number of TEG modules.
- K_{TEG} : Thermal conductivity of the TEG material (W/mK).
- A_{TE} : Cross-sectional area of the thermoelements (m²).
- N : Number of thermoelectric pairs in the module.
- L_{TE} : Length of the thermoelements (m).

- T_H and T_C : Hot and cold side temperatures of the TEG module (K).

The equation (5) shows that improving material properties (K_{TEG}, A_{TE}) or increasing the temperature gradient ($T_H - T_C$) can enhance the heat flux, driving better performance.

3.6 Total Electrical Power Output

The equation (6) represents the total power output of the PV-TEG hybrid system by summing contributions from both modules [28, 33].

$$P_{el} = P_{el,PV} + P_{el,TEG} \quad \dots (6)$$

It emphasizes the complementary nature of these components in capturing both solar and waste thermal energy for electricity generation.

3.7 System Efficiency

The equation (7) defines the electrical efficiency of the PV-TEG hybrid system as the ratio of total electrical power output to the incident solar energy, [6], [28].

$$\eta_{el} = \frac{P_{el}}{G \cdot A_{PV}} \quad \dots (7)$$

where:

- P_{el} : Total electrical power output (W).
- $G \cdot A_{PV}$: Total solar power incident on the PV module (W).

4. Case Studies

The various case studies referring to the different experimental setups, simulation-based investigations, or real-world prototype deployments involving hybrid PV-TEG systems, as summarized in Table 2 and Table 3.

Table 2: Key findings from different case studies and methodologies

Case Study	Methodology	Key Findings	Reference
Integration of Bismuth Telluride Modules	A hybrid PV–TEG system was developed by integrating bismuth telluride-based thermoelectric modules with polycrystalline silicon PV panels. Experimental tests and simulation analyses were conducted under varying thermal conditions.	In a hybrid setup using ten Bi ₂ Te ₃ TEG modules attached to the rear of a polycrystalline PV panel, thermal energy recovery led to a 5.5% reduction in PV operating temperature, resulting in a 19% increase in cumulative output power and a 17% rise in efficiency achieved through improved thermal coupling and effective waste heat utilization	M. A. I. Khan <i>et al.</i> , (2021) [29]
AOA Optimization for Hybrid PV–TEG Systems	The Arithmetic Optimization Algorithm (AOA) was applied for Maximum Power Point Tracking (MPPT) under Non-Uniform Temperature Distribution (NUTD). Real-time tracking and stabilization tests were performed to assess dynamic performance.	The Arithmetic Optimization Algorithm (AOA), inspired by basic arithmetic operations, was employed for Maximum Power Point Tracking (MPPT) in a hybrid PV–TEG system. The algorithm was implemented using MATLAB/Simulink simulations and validated through a low-cost TEG emulator integrated with a boost converter and an ATmega2560 microcontroller. A tracking efficiency of 99.86% was achieved, with an average stabilization time of 280 milliseconds and full settling observed within 0.42 seconds. During a 24-hour real-time simulation, an average power output of 465.3 W/h and a total energy yield of 11.15 kWh were recorded. The performance was found to surpass that of conventional techniques such as PSO, CSA, and GWO. These findings demonstrate that AOA provides a fast, accurate, and robust MPPT strategy suitable for hybrid PV–TEG systems.	A. F. Mirza <i>et al.</i> (2021) [30]
CFD Analysis with Passive Air Cooling	A three-dimensional Computational Fluid Dynamics (CFD) model was developed to simulate a PV–TEG system equipped with an integrated passive air heat sink. Environmental parameters such as wind speed and ambient temperature were varied to optimize cooling performance.	In the study CFD was used to simulate a PV–TEG hybrid system cooled via an air heat sink. Importantly, the study conducted a comprehensive mesh independence test using four different grid densities (8M to 19M cells), confirming numerical accuracy via grid convergence index and Courant–Friedrichs–Lewy (CFL) stability criteria. Boundary conditions, including varying wind speeds (1.42–12.2 m/s), solar irradiance (200–1200 W/m ²), and ambient temperatures (10–30°C).	A. Wodołański <i>et al.</i> (2021) [31]

Case Study	Methodology	Key Findings	Reference
FOFLC-Based MPPT Hybrid PV-TEG System	A hybrid PV-TEG energy system was designed by integrating a PV module with a thermoelectric generator mounted on its backside. An enhanced fractional order fuzzy logic controller (FOFLC)-based MPPT technique was developed and implemented.	The proposed FOFLC-based MPPT method achieved faster and more accurate MPP tracking, improving overall energy conversion efficiency by about 4.5% compared to standalone PV systems.	Kanagaraj N. <i>et al.</i> (2021) [32]
Case Study Combined PV + TEG System	The PV efficiency was modeled using a temperature-dependent equation, while the TEG performance was fitted using a quadratic function. Standard solar irradiance conditions were assumed, and the non-absorbed fractions of energy were taken into account. The heat flux available to the TEG was calculated based on the absorbed energy from the PV panel.	The study found that, for certain configurations, the combined PV-TEG system produced lower power than the PV panel alone. However, an increase in total power output was observed for a specific type of PV panel. It was also noted that the degradation of PV efficiency due to temperature rise had a more significant impact than the additional power gained from the TEG.	R. Bjørk and K. K. Nielsen (2015) [33]
Combine PV and TEG	The paper conducts a comprehensive literature review of prior experimental and numerical studies on hybrid PV TEG systems, focuses on both direct coupling (placing techs at the rear of PV modules) and spectrum splitting approaches (splitting solar wavelength so that PV absorbs part of the spectrum and TEG uses the remaining thermal portion).	Efficiency Gains: Integrating TEGs can increase total power output by converting excess heat from PV into electricity, leading to efficiency improvement of up to 10% or more, depending on the configuration. Thermal management: minimizing contact resistance (between PV TEG and heat sink) and providing effective cooling. E.g. phase-change material, heat pipes are critical to maintaining a sufficient temperature gradient across teg modules.	U. A. Saleh <i>et al.</i> (2021) [17]
Novel hybrid PV-MCHP-TEG system integrating a photovoltaic module, microchannel heat pipes, and a thermoelectric generator with a season-adaptive three-way valve	Development of energy and heat transfer models; simulation using MATLAB/Simulink to compare electrical performance and enviroeconomic metrics (e.g., CO ₂ reduction, payback period) with traditional PV and PV-TEG systems.	It was found that the PV-MCHP-TEG system was demonstrated to perform better than conventional PV and PV-TEG systems. Electrical efficiency was increased to 18.75%, power output was improved by up to 18.61%, CO ₂ emissions were reduced by 260 kg/year, and a shorter payback period of approximately 18.96 years was achieved.	Y. Zhang <i>et al.</i> (2023) [34]

Table 3: Comparative Table for various PV–TEG Hybrid System Configurations

Study	TEG Material	Cooling Method	MPPT/Control Algorithm	Validation Type	Power Output (W)	Efficiency / Tracking Performance (%)
A. F. Mirza <i>et al.</i> (2021) [30]	Bi_2Te_3 Emulator	Natural Convection	Arithmetic Optimization Algorithm (AOA)	Simulation + Hardware (TEG emulator + ATmega2560)	465.3	99.86 (tracking efficiency)
A. Wodołański <i>et al.</i> (2021) [31]	Bi_2Te_3	Air-cooled Heat Sink	None (CFD Simulation only)	CFD Co-simulation (Fluent–Simplorer)	430 (peak simulated)	~11.5 (system efficiency)
W. He <i>et al.</i> (2020) [13]	Bi_2Te_3	Forced Convection	Standard Incremental Conductance MPPT	Simulation (MATLAB/Simulink)	~350	10–12 (system efficiency)
X. Jia <i>et al.</i> (2020) [14]	PbTe	Phase Change Material	Fuzzy Logic MPPT	Simulation (COMSOL Multiphysics + MATLAB)	~480	13.2

5. Critical Evaluation and Comparative Analysis

A comparative analysis of different optimization techniques has been summarized in Table 2 and Table 3. Experimental integration of thermoelectric modules, provided a straightforward method for waste heat recovery and efficiency enhancement as demonstrated in [29]. This approach showed significant improvements in power output but was limited by the material properties of thermoelectric modules [29]. CFD modeling with passive cooling mechanisms, effectively addressed thermal management issues and improved efficiency under the varying environmental condition in [31].

This review of different studies offers important insights into PV–TEG hybrid system performance, but a deeper examination reveals a critical evaluation of methodological differences that affect result comparability, thereby revealing practical research gaps. For instance, A. F. Mirza *et al.* [30] validated their AOA-based MPPT strategy through both simulation and hardware testing under dynamic conditions, achieving high efficiency and stability. In contrast, A. Wodołański *et al.* [31] focused on CFD-based modeling without experimental validation, limiting practical relevance despite robust thermal analysis. Material selection was another key variable - Bi_2Te_3 was commonly used for its stability at low to mid temperatures, yet limited comparative work exists involving materials like PbTe or TAGS, which perform better at higher thermal gradients. Similarly, advanced MPPT algorithms like AOA and fuzzy logic outperformed

traditional approaches in simulations but lacked real-world testing. Moving forward, standardized benchmarking, comparative analysis, and consistent validation methods are essential for reliable performance evaluation across studies.

6. Conclusion

The integration of photovoltaic (PV) and thermoelectric generator (TEG) systems is a promising path for the enhancement of energy conversion through solar radiation and waste heat. Significant advancements in thermoelectric material performance improvement, thermal management systems optimization, and refinement in system designs have been achieved that can enhance energy output and overall efficiency.

Despite these advances, many issues still need to be addressed. The compatibility of newer technologies such as multi-junction tandem cells and spectrum splitting with PV–TEG needs to be further explored. More importantly, there is an urgent need for the development of thermoelectric materials with high Seebeck coefficients, low thermal conductivity, and effective thermal interfaces. Thermal management is also a critical area since maintaining stable temperature differentials across TEG modules and minimizing heat accumulation in PV panels are required for optimum performance.

Future research should, therefore, focus on advanced materials, hybrid cooling mechanisms,

and modular architectures of the system. Strong collaboration between material science and thermal engineering with photovoltaic technology will be needed in order to overcome the prevailing limitations. PV-TEG hybrid systems, which continue to improve and strategize, hold significant potential toward developing sustainable and efficient energy solutions.

References

- [1] A. Qazi *et al.*, "Towards Sustainable Energy: A Systematic Review of Renewable Energy Sources, Technologies, and Public Opinions," *IEEE Access*, vol. 7, pp. 63837–63851, 2019, doi: 10.1109/ACCESS.2019.2906402.
- [2] S. Mekhilef, R. Saidur, and A. Safari, "A review on solar energy use in industries," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 4, pp. 1777–1790, May 2011, doi: 10.1016/j.rser.2010.12.018.
- [3] S. P. Aly, S. Ahzi, and N. Barth, "Effect of physical and environmental factors on the performance of a photovoltaic panel," *Solar Energy Materials and Solar Cells*, vol. 200, p. 109948, Sep. 2019, doi: 10.1016/j.solmat.2019.109948.
- [4] H. Jouhara *et al.*, "Thermoelectric generator (TEG) technologies and applications," *International Journal of Thermofluids*, vol. 9, p. 100063, Feb. 2021, doi: 10.1016/j.ijft.2021.100063.
- [5] S. N. M. Tawil and M. Z. Zainal, "Energy harvesting using TEG and PV cell for low power application," in *Proc. of International Conference on Engineering and Technology (IntCET 2017), Putrajaya, Malaysia, AIP Conf. Proc.*, 2018, vol 1930, no. 1, p. 020041. doi: 10.1063/1.5022935
- [6] A. Z. Sahin, K. G. Ismaila, B. S. Yilbas, and A. Al-Sharafi, "A review on the performance of photovoltaic/thermoelectric hybrid generators," *Int J Energy Res*, vol. 44, no. 5, pp. 3365–3394, Apr. 2020, doi: 10.1002/er.5139.
- [7] N. Wang, L. Han, H. He, N.-H. Park, and K. Koumoto, "A novel high-performance photovoltaic–thermoelectric hybrid device," *Energy Environ. Sci.*, vol. 4, no. 9, p. 3676, 2011, doi: 10.1039/c1ee01646f.
- [8] Z. Usman, J. Tah, H. Abanda, and C. Nche, "A Critical Appraisal of PV-Systems' Performance," *Buildings*, vol. 10, no. 11, p. 192, Oct. 2020, doi: 10.3390/buildings10110192.
- [9] Y. Sheikh, M. Jasim, M. Qasim, A. Qaisieh, M. O. Hamdan, and F. Abed, "Enhancing PV solar panel efficiency through integration with a passive Multi-layered PCMs cooling system: A numerical study," *International Journal of Thermofluids*, vol. 23, p. 100748, Aug. 2024, doi: 10.1016/j.ijft.2024.100748.
- [10] E. E. Van Dyk, A. R. Gxasheka, and E. L. Meyer, "Monitoring current–voltage characteristics and energy output of silicon photovoltaic modules," *Renewable Energy*, vol. 30, no. 3, pp. 399–411, Mar. 2005, doi: 10.1016/j.renene.2004.04.016.
- [11] S. Twaha, J. Zhu, Y. Yan, and B. Li, "A comprehensive review of thermoelectric technology: Materials, applications, modelling and performance improvement," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 698–726, Nov. 2016, doi: 10.1016/j.rser.2016.07.034.
- [12] O. H. Ando Junior, N. H. Calderon, and S. S. De Souza, "Characterization of a Thermoelectric Generator (TEG) System for Waste Heat Recovery," *Energies*, vol. 11, no. 6, p. 1555, Jun. 2018, doi: 10.3390/en11061555.
- [13] W. He, R. Guo, S. Liu, K. Zhu, and S. Wang, "Temperature gradient characteristics and effect on optimal thermoelectric performance in exhaust power-generation systems," *Applied Energy*, vol. 261, p. 114366, Mar. 2020, doi: 10.1016/j.apenergy.2019.114366.
- [14] X. Jia and Q. Guo, "Design study of Bismuth-Telluride-based thermoelectric generators based on thermoelectric and mechanical performance," *Energy*, vol. 190, p. 116226, Jan. 2020, doi: 10.1016/j.energy.2019.116226.
- [15] A. Z. Sahin, K. G. Ismaila, B. S. Yilbas, and A. Al-Sharafi, "A review on the performance of photovoltaic/thermoelectric hybrid generators," *Int J Energy Res*, vol. 44, no. 5, pp. 3365–3394, Apr. 2020, doi: 10.1002/er.5139.
- [16] G. Li, S. Shittu, T. M. O. Diallo, M. Yu, X. Zhao, and J. Ji, "A review of solar

- photovoltaic-thermoelectric hybrid system for electricity generation,” *Energy*, vol. 158, pp. 41–58, Sep. 2018, doi: 10.1016/j.energy.2018.06.021.
- [17] U. A. Saleh, M. A. Johar, S. A. B. Jumaat, M. N. Rejab, and W. A. W. Jamaludin, “Evaluation of a PV-TEG Hybrid System Configuration for an Improved Energy Output: A Review,” *International Journal of Renewable Energy Development*, vol. 10, no. 2, pp. 385–400, May 2021, doi: 10.14710/ijred.2021.33917.
- [18] R. Moshwan *et al.*, “Advances and challenges in hybrid photovoltaic-thermoelectric systems for renewable energy,” *Applied Energy*, vol. 380, p. 125032, Feb. 2025, doi: 10.1016/j.apenergy.2024.125032.
- [19] D. Sanin-Villa, “Recent Developments in Thermoelectric Generation: A Review,” *Sustainability*, vol. 14, no. 24, p. 16821, Dec. 2022, doi: 10.3390/su142416821.
- [20] Y. Gao, Z. Dai, D. Wu, C. Wang, B. Chen, and X. Zhang, “Transient performance assessment of a hybrid PV-TEG system integrated with PCM under non-uniform radiation conditions: A numerical investigation,” *Renewable Energy*, vol. 198, pp. 352–366, Oct. 2022, doi: 10.1016/j.renene.2022.08.087.
- [21] A. Makki, S. Omer, Y. Su, and H. Sabir, “Numerical investigation of heat pipe-based photovoltaic-thermoelectric generator (HP-PV/TEG) hybrid system,” *Energy Conversion and Management*, vol. 112, pp. 274–287, Mar. 2016, doi: 10.1016/j.enconman.2015.12.069.
- [22] S. Sripadmanabhan Indira *et al.*, “A review on various configurations of hybrid concentrator photovoltaic and thermoelectric generator system,” *Solar Energy*, vol. 201, pp. 122–148, May 2020, doi: 10.1016/j.solener.2020.02.090.
- [23] A. Kumar, S. Bano, B. Govind, A. Bhardwaj, K. Bhatt, and D. K. Misra, “A Review on Fundamentals, Design and Optimization to High ZT of Thermoelectric Materials for Application to Thermoelectric Technology,” *J. Electron. Mater.*, vol. 50, no. 11, pp. 6037–6059, Nov. 2021, doi: 10.1007/s11664-021-09153-7.
- [24] M. Gopinath and R. Marimuthu, “PV-TEG output: Comparison with heat sink and graphite sheet as heat dissipators,” *Case Studies in Thermal Engineering*, vol. 45, p. 102935, May 2023, doi: 10.1016/j.csite.2023.102935.
- [25] A. M. Law, L. O. Jones, and J. M. Walls, “The performance and durability of Anti-reflection coatings for solar module cover glass – a review,” *Solar Energy*, vol. 261, pp. 85–95, Sep. 2023, doi: 10.1016/j.solener.2023.06.009.
- [26] M. Kamran Khan, M. Hamza Zafar, M. Mansoor, A. Feroz Mirza, U. Amir Khan, and N. Mujeeb Khan, “Green energy extraction for sustainable development: A novel MPPT technique for hybrid PV-TEG system,” *Sustainable Energy Technologies and Assessments*, vol. 53, p. 102388, Oct. 2022, doi: 10.1016/j.seta.2022.102388.
- [27] K. Teffah and Y. Zhang, “Modeling and experimental research of hybrid PV-thermoelectric system for high concentrated solar energy conversion,” *Solar Energy*, vol. 157, pp. 10–19, Nov. 2017, doi: 10.1016/j.solener.2017.08.017.
- [28] A. A. Salbookh, M. W. Aljibory and H. T. Hashim, “Numerical and Experimental Comparison of Passive Cooling Effect on Photovoltaic- Thermoelectric Generator hybrid System,” *Performance. Current Research on Engineering*, vol. 9, no. 1, pp. – 63-88. Available: <https://www.jocrest.com/dergi/numerical-and-experimental-comparison-of-passive-cooling-effect-on-photovoltaic-thermoelectric-generator-hybrid-system-performance20230624110454.pdf>
- [29] M. A. I. Khan *et al.*, “An Experimental and Comparative Performance Evaluation of a Hybrid Photovoltaic-Thermoelectric System,” *Front. Energy Res.*, vol. 9, p. 722514, Sep. 2021, doi: 10.3389/fenrg.2021.722514.
- [30] A. F. Mirza, M. Mansoor, K. Zerbakht, M. Y. Javed, M. H. Zafar, and N. M. Khan, “High-efficiency hybrid PV-TEG system with intelligent control to harvest maximum energy under various non-static operating conditions,” *Journal of Cleaner Production*, vol. 320, p. 128643, Oct. 2021, doi: 10.1016/j.jclepro.2021.128643.
- [31] A. Wodolązski, N. Howaniec, B. Jura, A. Bąk, and A. Smoliński, “CFD Numerical Modelling of a PV-TEG Hybrid System Cooled by Air Heat Sink Coupled with a Single-Phase Inverter,” *Materials*, vol. 14, no. 19, p. 5800, Oct. 2021, doi: 10.3390/ma14195800.

- [32] Kanagaraj N, "Photovoltaic and Thermoelectric Generator Combined Hybrid Energy System with an Enhanced Maximum Power Point Tracking Technique for Higher Energy Conversion Efficiency," *Sustainability*, vol. 13, no. 6, p. 3144, Mar. 2021, doi: 10.3390/su13063144.
- [33] R. Bjørk and K. K. Nielsen, "The performance of a combined solar photovoltaic (PV) and thermoelectric generator (TEG) system," *Solar Energy*, vol. 120, pp. 187–194, Oct. 2015, doi: 10.1016/j.solener.2015.07.035.
- [34] Y. Zhang, N. Zhu, X. Zhao, Z. Luo, P. Hu, and F. Lei, "Energy performance and enviroeconomic analysis of a novel PV-MCHP-TEG system," *Energy*, vol. 274, p. 127342, Jul. 2023, doi: 10.1016/j.energy.2023.127342.

Dr. Bani Kanta Talukdar

received his B.E. degree Electrical Engineering from Gauhati University, Assam India, his M.Sc. degree in Electrical Engineering from University of Saskatchewan, Canada and his Ph.D. from Indian Institute of Technology, Kharagpur, India. Presently he is working as Professor in Electrical Engineering, Assam Engineering College, Guwahati under Assam Science and Technology University. He has more than 20 journal and conference publications. His research interest includes, Electrical Power System, Congestion Management in Power Network, Smart Grid Computations. He can be reached at email: bktalukdar.ele@aec.ac.in



Authors' Profiles

Pallavi Roy is an Assistant Professor in the Department of Electrical Engineering at Girijananda Chowdhury University, Guwahati, Assam, India. She holds a Master of Technology (M.Tech.) in Energy Technology from Tezpur University, where she graduated as the gold medalist of the 2012-14 batch. Her excellence was further acknowledged through the ONGC scholarship for being the topper in her M.Tech. Program. Her work during her M.Tech. was part of the UK-India Education and Research Initiative (UKIERI) funded project in collaboration with the University of Nottingham. She has supervised more than 10 B.Tech. students. She can be contacted at email: pallavi_ee@gcuniversity.ac.in



Aditya Roy is currently a student of B.Tech. 8th Semester, Electrical Engineering, at Girijananda Chowdhury Institute of Management and Technology, Assam, India.

