

# Thermoelectric Generator for Waste Heat Recovery System

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## Abstract

The growing demand for sustainable energy solutions has intensified interest in recovering waste heat to reduce energy losses in automotive and industrial systems. In this study, a thermoelectric generator (TEG) system was designed, modelled, and experimentally validated to convert waste heat into electrical energy using the Seebeck effect. Thermoelectric modules were selected based on a high Seebeck coefficient and low thermal conductivity to minimize energy losses while maintaining a large temperature gradient across the system. Thermal and electrical performance of the TEG system under varying operating conditions was analysed using ANSYS and MATLAB Multiphysics simulations. Experimental validation demonstrated a maximum electrical power output of 3.0 W and a peak thermal-to-electrical conversion efficiency of 6.0% at a temperature differential of 350 °C. The results indicate that compact thermoelectric generator systems can serve as reliable, maintenance-free, and decentralized power sources for waste heat recovery in automotive exhausts and industrial processes. Although conversion efficiency and power management remain key challenges for thermoelectric technologies, the findings highlight their significant potential for clean energy harvesting from medium-to high-grade waste heat sources.

**Keywords:** Waste Heat Recovery, Thermoelectric Recovery, Thermoelectric Generator (TEG), Energy Conversion Efficiency, Thermoelectric Modules, High Temperature Gradient, Low Thermal Conductivity, Power Output, Automotive Applications, Industrial Applications, Clean Energy Solution

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## 1. Introduction

The rapid growth in global energy consumption, coupled with increasing environmental concerns, has made efficient energy utilization a critical engineering challenge. A significant proportion of primary energy input in industrial facilities, thermal power plants, and automotive engines is dissipated as waste heat. Studies indicate that nearly 60–70% of the total fuel energy consumed in such systems is lost to the environment in the form of unused thermal energy [1]. Recovering even a fraction of this waste heat and converting it into usable electrical power can substantially improve overall system efficiency while simultaneously reducing greenhouse gas emissions.

Thermoelectric generators (TEGs) present a promising solution for direct waste heat recovery due to their ability to convert thermal energy into electrical energy using the Seebeck

effect [2]. When a temperature gradient is maintained across a thermoelectric material, an electrical voltage is generated without the need for moving components. This solid-state operating principle results in silent operation, high reliability, compact system design, and minimal maintenance requirements, making TEGs particularly suitable for decentralized and space-constrained applications.

In recent years, extensive research has explored the application of thermoelectric generators for waste heat recovery in automotive exhaust systems. Experimental and numerical studies have demonstrated that TEGs integrated with engine exhausts can generate electrical power ranging from a few watts to several hundred watts, depending on the temperature gradient, system configuration, and material properties [3], [4]. Similarly, industrial applications such as furnaces, boilers, and marine engines offer substantial potential for TEG deployment due to the availability of sustained high-temperature heat sources [5], [6].

The advancement of thermoelectric materials has played a key role in enhancing the performance of TEG systems. The introduction of high-figure-of-merit ( $ZT$ ) materials, nanostructured compounds, and optimized material compositions has contributed to measurable improvements in conversion efficiency and operational stability [7], [8]. Despite these advancements, commercially available thermoelectric systems typically exhibit conversion efficiencies below 10%, which remains a primary limitation to widespread adoption [9], [10]. In addition, high material costs, system integration challenges, and thermal management constraints continue to restrict large-scale commercial implementation [11], [12].

The performance of a thermoelectric generator is strongly influenced by the temperature gradient maintained between its hot and cold junctions. Efficient heat transfer at the hot side and effective cooling at the cold side are therefore essential for maximizing power output and conversion efficiency [13], [14]. Furthermore, long-term mechanical and thermal reliability of TEG modules under cyclic and high-temperature operating conditions remains an important area of investigation, particularly for automotive and industrial environments [15], [16].

Several experimental and analytical studies have focused on the design and testing of TEG-based systems for effective waste heat recovery [18]–[20]. Recent research has increasingly emphasized the use of combined experimental and simulation-based approaches to optimize material selection, system geometry, and thermal interfaces under realistic operating conditions [21]–[23]. These studies highlight the importance of integrated thermal-electrical modelling for predicting system performance and identifying opportunities for efficiency enhancement.

In this context, the present work focuses on the design, modelling, and experimental validation of a thermoelectric generator system intended for waste heat recovery from automotive and industrial heat sources. The study aims to evaluate system performance under varying temperature gradients, assess material suitability, and validate simulation results through experimental testing. By adopting a systematic and documented approach, this research contributes toward the development of compact, low-profile, and reliable thermoelectric systems capable of

decentralized waste heat energy harvesting from exhaust gases and flue streams [25]–[30].

## 2. Methodology

This study adopts a research-based approach to evaluate the performance of thermoelectric generators (TEGs) for waste heat recovery applications. The methodology focuses on understanding the fundamental operating principles of TEGs, with particular emphasis on thermoelectric material selection and system design considerations. Existing thermoelectric module configurations were analysed to assess their electrical and thermal performance under varying temperature gradients. In addition, the applicability of TEG systems across different industrial sectors, including automotive, manufacturing, and electronic systems, was examined through analytical evaluation, numerical modelling, and experimental investigation.

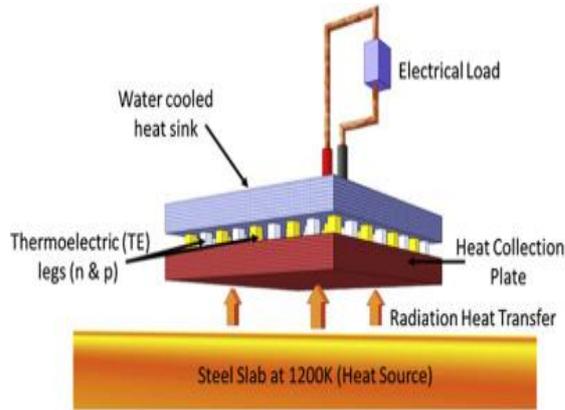
## 3. System Design and Configuration

The thermoelectric generator (TEG) system developed in this study is designed to recover waste thermal energy from high-temperature sources such as automotive exhaust pipes, industrial flue gases, and engine blocks, and convert it into electrical energy. The system comprises multiple integrated components that operate synchronously to achieve stable and efficient energy conversion.

A high thermal conductivity metallic interface plate is used at the heat source to ensure effective heat transfer to the hot side of the thermoelectric module. Thermoelectric modules are selected based on key material properties, including a high Seebeck coefficient, suitable operating temperature limits, and low thermal conductivity to maintain a strong temperature gradient across the module. Materials such as bismuth telluride ( $\text{Bi}_2\text{Te}_3$ ) and lead telluride ( $\text{PbTe}$ ) are considered due to their established thermoelectric performance within the targeted temperature range.

To sustain the temperature difference required for power generation, a heat sink or active cooling mechanism is employed at the cold side of the thermoelectric module. Effective thermal management at this interface is essential for minimizing heat losses and improving electrical output. The electrical power generated by the

thermoelectric module is conditioned using a power management circuit, typically incorporating a DC–DC converter, to regulate voltage levels and ensure compatibility with practical electrical loads and energy storage systems.



**Figure 1:** Schematic of thermoelectric generator system [1]

## 4. Equations

### Seebeck Voltage Generation

The electrical voltage generated across a thermoelectric material due to a temperature difference ( $\Delta T$ ) between its hot and cold junctions is governed by the Seebeck effect and is expressed as:

$$V = \alpha \Delta T \quad (1)$$

where,  $\alpha$  is the Seebeck coefficient of the thermoelectric material.

### Electrical Power Output

The electrical power output of a thermoelectric generator (TEG) connected to an external load can be calculated using:

$$p = \left[ \frac{V^2}{(R_{load} + R_{int})} \right] \quad (2)$$

where  $R_{load}$  is the external load resistance and  $R_{int}$  is the internal electrical resistance of the thermoelectric module.

More generally, the power output can be expressed as:

$$P = \frac{(\alpha \Delta T)^2}{R} \quad (3)$$

where  $R$  represents the effective electrical resistance of the system.

### Efficiency of Thermoelectric Generator

The thermal-to-electrical conversion efficiency  $\eta$  of a thermoelectric generator is given by:

$$\eta = \left( \frac{P_{out}}{Q_{in}} \right) = \left( \frac{\Delta T}{T_{hot}} \right) \cdot \left( \frac{(\sqrt{1 + ZT_{avg}} - 1)}{(\sqrt{1 + ZT_{avg}} + \frac{T_{cold}}{T_{hot}})} \right) \quad (4)$$

where  $T_{hot}$  and  $T_{cold}$  are the absolute temperatures of the hot and cold junctions, respectively, and  $ZT_{avg}$  is the average figure of merit over the operating temperature range.

### Figure of Merit (ZT)

The performance of thermoelectric materials is characterized by the dimensionless figure of merit  $ZT$ , which is defined as:

$$ZT = \frac{(\alpha^2 \sigma T)}{\kappa} \quad (5)$$

where  $\sigma$  is the electrical conductivity,  $T$  is the absolute temperature, and  $\kappa$  is the thermal conductivity of the material.

These equations form the theoretical foundation for modelling and analysing the performance of the thermoelectric generator under varying waste heat conditions.

They were integrated into analytical calculations and numerical simulation tools during the system design, optimization, and evaluation phases.

## 5. Material Selection

Material selection for the thermoelectric generator (TEG) system was guided by the objective of maximizing overall system performance under practical operating conditions. Key selection criteria included a high Seebeck coefficient to enhance voltage generation, low thermal conductivity to maintain a strong temperature gradient across the thermoelectric module, and adequate electrical conductivity to facilitate efficient charge carrier transport. In addition, thermal stability at the intended operating temperature range was considered essential to ensure reliable and continuous performance under fluctuating heat input conditions.

For experimental evaluation and system integration, commercially available TEC1-12706 thermoelectric modules were selected. These modules were chosen due to their established performance characteristics,

availability, and suitability for medium temperature gradient applications. Their use enabled effective assessment of system feasibility, performance trends, and integration challenges in waste heat recovery applications.

## 6. Modelling and Simulation

A system model was created, and the operational thermal and electrical performance was predicted by conducting simulations using ANSYS and MATLAB. The simulations analysed the thermal distribution within the system and predicted the output voltage, generated power, and system efficiency across a range of temperatures. The simulation parameters were precisely defined and reliably controlled for hot-side temperatures between 200–400 °C and cold-side temperatures between 25–50 °C. The model also accounted for thermal contact resistances within system components and convective heat losses to the surrounding environment. These simulations provided valuable insights into the functioning of the thermoelectric generator system while identifying areas for potential performance optimization.

## 7. Experimental Validation

Validating of the prototype system simulation involved multiple trials and experimental testing of the system's heat input. The experiments included measurement of heat flux input, as well as the corresponding power, current, and voltage at both the input and output. The analysis of waste heat-to-electricity generation for the prototype system was based on the efficiency calculated using the relation ( $Efficiency = Output\ Electrical\ Power / Input\ Thermal\ Energy$ ). This evaluation was performed using the measured values and the described area analysis.

## 8. Data Analysis

Model verification was carried out to assess the consistency between experimental and simulated results under varying operating conditions. Performance trends were analysed to identify the underlying factors influencing system behaviour, primarily temperature differences and gradients, material properties, and heat losses across the system. Verification of the findings, including the application of statistical methods and error checks, enabled a thorough comparison between simulated and experimental data, thereby validating the

overall reliability and accuracy of the research outcomes. The data analysed also supported the effectiveness of the modelling approach in predicting system performance and provided confidence in the repeatability of the experimental results.

## 9. Results and Discussion

### Overview of Experimental and Simulation Data

The thermoelectric generator system was analysed over temperature differences ranging from 50 °C to 350 °C, corresponding to common waste heat conditions in automotive and industrial environments. The experimental investigation determined both the electrical power output and the corresponding thermal-to-electrical conversion efficiency. The following table summarizes the key findings::

| Temperature Gradient (°C) | Power Output (W) | Efficiency (%) |
|---------------------------|------------------|----------------|
| 50                        | 0.2              | 1.5            |
| 100                       | 0.6              | 2.5            |
| 150                       | 1.1              | 3.8            |
| 200                       | 1.6              | 4.5            |
| 250                       | 2.1              | 5.2            |
| 300                       | 2.6              | 5.6            |
| 350                       | 3.0              | 6.0            |

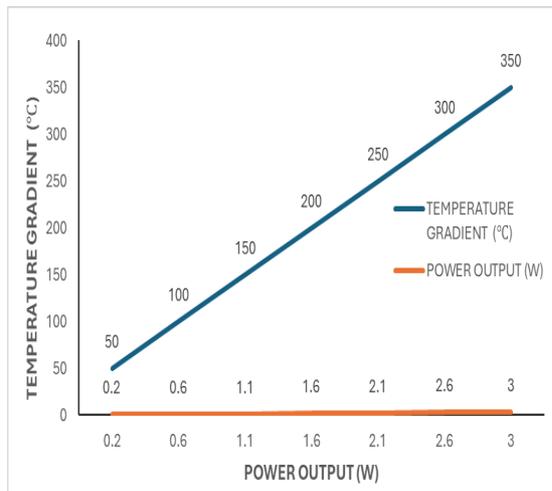
### Thermal Performance and Power Output

To calculate the operational efficiency of the thermoelectric generator, experimental testing alongside simulations was carried out across different temperature differentials ranging from 50 °C to 350 °C. Higher temperature differences across the hot and cold sides of the TEG consistently improved electrical power generation and conversion efficiency. At a temperature differential of 50 °C, the system generated approximately 0.2 W of electrical power. At a hot-side temperature of 350 °C, the TEG achieved a maximum power output of 3.0 W. The thermal-to-electrical conversion efficiency reached 1.5% at the lowest temperature gradient and increased to 6.0% at higher gradients, demonstrating that the system is more effective under conditions of high thermal gradients typically found in engineered exhaust systems. These results indicate that the system is suitable for energy recovery applications involving thermal gradients similar to those present in industrial flue gas subsystems.

## 10. Graphical Representation

### Power Output

As the temperature difference increased, the electrical power output rose steadily, reaching 3.0 W at a temperature differential of 350 °C. This trend indicates a consistent increase in power generation with higher thermal gradients. Thermoelectric generators can effectively utilize waste heat at medium and high temperature levels, particularly in engine exhaust systems, industrial furnaces, and other heat-producing applications. Literature indicates that power generation is maximized at higher thermal gradients; however, practical challenges arise at the heat-receiving interfaces. Issues such as material degradation due to elevated temperatures and inadequate heat dissipation are associated with improper thermal interfaces. Realizing the full potential of TEG-based systems requires the use of high-temperature-resilient materials, refined thermal interfaces, and effective cooling systems.

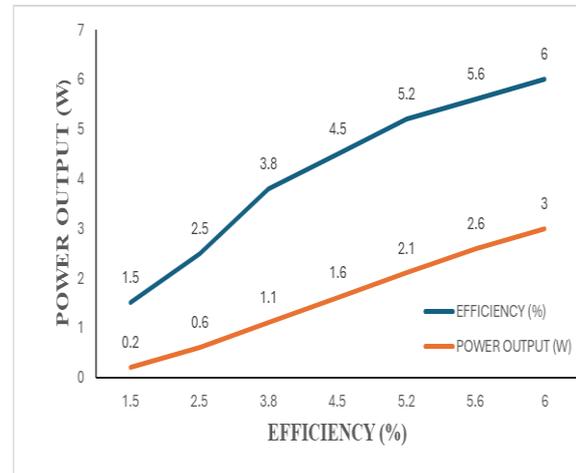


**Graph 1 :** Variation of electrical power output with temperature gradient

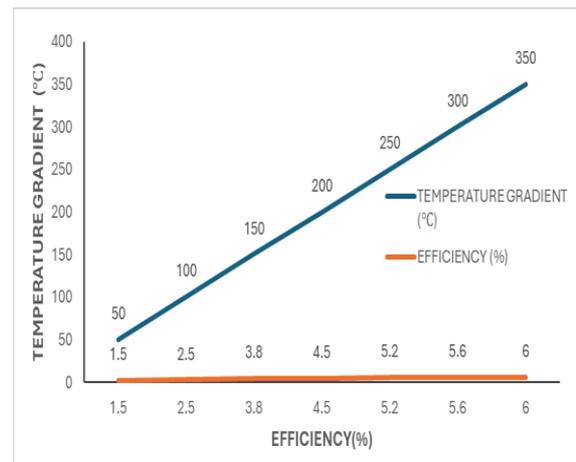
### Efficiency

Performance measurements showed an increase in efficiency from 1.5% to 6.0%, which is consistent with the standard performance of commercial thermoelectric modules fabricated from bismuth telluride ( $\text{Bi}_2\text{Te}_3$ ). Beyond a temperature gradient of 250 °C, the system exhibited an efficiency plateau, as further increases in temperature difference resulted in

only marginal efficiency improvement. This observation indicates that  $\text{Bi}_2\text{Te}_3$ -based materials experience performance limitations at higher temperatures, thereby motivating the exploration of alternative thermoelectric materials such as lead telluride ( $\text{PbTe}$ ) and nanostructured compounds to enhance waste heat recovery system performance.



**Graph 2 :** Power Output Vs Efficiency



**Graph 3 :** Temperature gradient Vs Efficiency

## Comparative Analysis

Thermoelectric generators (TEGs) offer several advantages over conventional waste heat recovery systems, including Rankine and Organic Rankine cycle technologies, despite their relatively lower conversion efficiency. TEGs are compact, stationary devices with no moving components, which enables reliable operation and eliminates the need for frequent maintenance. Although their conversion efficiency is lower than that of traditional

systems, TEGs are well suited for applications where system integration is straight-forward, and space availability is limited. Additionally, TEGs are effective for recovering low-grade waste heat and are particularly suitable for operation in the confined environments of automotive exhaust systems and localized industrial heat sources.

## 11. Conclusion

These results indicate a high potential for thermoelectric generators (TEGs) in waste heat recovery across a wide temperature range in automotive and industrial applications. Both the mechanisms of power generation and the performance ratios in thermal-to-electrical conversion showed continuous improvement, attributed to experimentally and numerically modelled increases in temperature gradients. A peak power output of 3.0 W along with an efficiency of 6.0% at an operating temperature gradient of 350 °C indicates potential applicability in engine exhaust and industrial steam flow systems. However, TEG systems for high-temperature applications still require further performance improvement, along with advancements in resource utilization and thermal management. More effective TEGs will require improved construction materials, enhanced thermal resistance research, and advanced cooling techniques. Although TEGs recover heat less effectively than traditional Rankine cycle systems, their compact design, reliable operation, and zero-maintenance characteristics establish them as valuable solutions for decentralized and low-grade waste heat recovery. Utilizing waste heat to generate usable electricity through thermoelectric generators presents an effective pathway toward sustainable energy solutions across various industrial sectors.

## References

- [1] N. Jaziri, A. B. Amoura, J. Müller, B. Meghani, F. Tounsi, and M. Ismail, "A comprehensive review of thermoelectric generators: Technologies and common applications," *Energy Reports*, vol. 6, pp. 264–287, Dec. 2020.
- [2] J. G. Haidar and J. I. Gohel, "Waste heat recovery from the exhaust of low-power diesel engine using thermoelectric generators," in *Proc. Int. Conf. Thermoelectric (ICT)*, 2001, pp. 413–418.
- [3] P. Roy, P. Choudhury, and P. J. Bodo, "Modeling and design of a thermoelectric generator for waste heat recovery," in *Proc. Int. Conf. Computational Performance Evaluation (ComPE)*, 2021, pp. 854–857.
- [4] R. Rodriguez, M. Preindl, J. S. Cotton, and A. Emadi, "Review and trends of thermoelectric generator heat recovery in automotive applications," *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 5366–5378, Jun. 2019.
- [5] M. Saha, O. Tregenza, J. Twelvetrees, and C. Holston, "A review of thermoelectric generators for waste heat recovery in marine applications," *Sustain. Energy Technol. Assess.*, vol. 59, Oct. 2023.
- [6] A. G. Olavi *et al.*, "Potential applications of thermoelectric generators in waste heat recovery systems," *Int. J. Thermofields*, vol. 16, Nov. 2022.
- [7] S. L. Jame and G. J. R. Kumar, "A comprehensive review on thermoelectric generators for energy harvesting," *Lect. Notes Electr. Eng.*, vol. 700, pp. 1897–1905, 2021.
- [8] N. V. Burnete, F. M. Siu, C. Decic, I. Barabas, and D. Moldovanu, "Review of thermoelectric generation for internal combustion engine waste heat recovery," *Prog. Energy Combust. Sci.*, vol. 91, Jul. 2022.
- [9] A. O. Ochieng, T. F. Megahed, S. Okwara, and H. Hassan, "Waste heat recovery using thermoelectric generators: A comprehensive review," *Process Saf. Environ. Prot.*, vol. 162, pp. 134–154, Jun. 2022.
- [10] L. Kutt and M. Lehtonen, "Automotive waste heat harvesting using thermoelectric systems," in *Proc. Int. Conf. Power Eng., Energy Electr. Drives*, Sep. 2015, pp. 55–62.
- [11] C. R. Kumar, A. S. Thalia, and R. Goel, "Experimental study on waste heat recovery from an internal combustion engine using thermoelectric technology," *Thermal Science*, vol. 15, no. 4, pp. 1011–1022, 2011.
- [12] R. Aridi, J. Faraj, S. Ali, T. Lemerand, and M. Khaled, "Thermoelectric power generators: State-of-the-art, heat recovery methods, and challenges," *Electricity*, vol. 2, no. 3, pp. 359–386, Sep. 2021.
- [13] N. R. Kristiansen, G. J. Snyder, H. K. Nielsen, and L. Rosendahl, "Waste heat recovery from a marine waste incinerator using a thermoelectric generator," *J.*

- Electron. Mater.*, vol. 41, no. 6, pp. 1024–1029, Jun. 2012.
- [14] B. I. Ismail and W. H. Ahmed, “Thermoelectric power generation using waste heat as a green technology,” *Recent Pat. Electr. Eng.*, vol. 2, no. 1, pp. 27–39, Jan. 2009.
- [15] S. H. Zaferani, M. Jafarian, D. Lashae, and R. Ghomeshi, “Thermal management and waste heat recycling using thermoelectric generators: An overview,” *Energies*, vol. 14, no. 18, Sep. 2021.
- [16] C. Wu, “Analysis of waste-heat thermoelectric power generators,” *Appl. Therm. Eng.*, vol. 16, no. 1, pp. 63–69, 1996.
- [17] L. S. Hawassa, A. S. Jayasena, M. M. M. Afnan, R. A. C. P. Ranasinghe, and M. A. Wijewardena, “Waste heat recovery using thermoelectric generators,” *Energy Reports*, vol. 6, pp. 474–479, Feb. 2020.
- [18] D. Saipraasad, S. Harish, R. Gopalan, and G. Sundararajan, “Automotive waste heat recovery by thermoelectric generator technology,” in *Bringing Thermoelectricity into Reality*, Jul. 2018.
- [19] H. Zhang, J. Liu, and Y. Wang, “Recent progress in thermoelectric materials and devices for waste heat recovery,” *Renew. Sustain. Energy Rev.*, vol. 185, p. 113502, 2023.
- [20] M. Zebarjadi, A. Shakouri, and J. He, “Advances in nanostructured thermoelectric materials: Performance and applications,” *Nat. Rev. Mater.*, vol. 8, pp. 25–41, 2023.
- [21] A. Al-Mahachi, R. S. Al-Zubaidi, and K. A. Ameer, “Optimization of automotive thermoelectric generators using CFD and genetic algorithms,” *Appl. Therm. Eng.*, vol. 241, p. 120098, 2024.
- [22] Y. Lu, S. Lin, and X. Zhang, “Flexible thermoelectric generators for low-grade waste heat recovery,” *Nano Energy*, vol. 110, p. 108422, 2024.
- [23] S. J. Lee and K. H. Park, “Performance enhancement of hybrid thermoelectric generator systems in exhaust heat recovery,” *Energy Convers. Manag.*, vol. 293, p. 118486, 2023.
- [24] R. Sakamoto, N. Sakamoto, and K. Takahashi, “Durability and efficiency evaluation of thermoelectric generators in high-temperature furnaces,” *J. Energy Eng.*, vol. 150, no. 4, 2024.
- [25] F. S. Ahmed, S. Kumar, and M. Pandey, “CFD analysis and experimental validation of diesel engine exhaust waste heat recovery using thermoelectric generators,” *J. Cleaner Prod.*, vol. 405, p. 137022, 2023.
- [26] T. W. Kim, D. Y. Park, and J. M. Lee, “Advanced Bi<sub>2</sub>Te<sub>3</sub> and PbTe-based hybrid modules for thermoelectric power generation,” *J. Electron. Mater.*, vol. 53, no. 7, pp. 4667–4678, 2024.
- [27] Z. Chen and L. Wei, “Development of skutterudite-based materials for high-temperature thermoelectric generators,” *Acta Materialia*, vol. 260, p. 119422, 2024.
- [28] M. H. Farooq, A. Z. Khan, and S. A. Malik, “Comparative study of Rankine cycle and thermoelectric generator-based waste heat recovery systems,” *Energy Reports*, vol. 11, pp. 2240–2255, 2025.
- [29] L. Z. Zhang, “Thermal design and optimization of thermoelectric generators for vehicle exhaust systems,” *Applied Energy*, vol. 350, p. 121909, 2024.
- [30] D. K. Sharma and P. Kumar, “Impact of contact resistance and temperature fluctuations on thermoelectric generator performance,” *Energy Convers. Manag.*, vol. 285, p. 117002, 2023.

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