

Performance Evaluation of Thermoelectric Generator Based Waste Heat Recovery system in Industrial Water Tube Boilers

Dr. Kapil Rambhau Aglawe¹, Dr. Shrikant Madhavrao Awatade², Tushar Vinod Bankar³, Ashish Anant Sarkate⁴, Chetan Babarao Khune⁵, Nikhil Gajanan Parshuramkar⁶, Rahul Tap Singh Pardhi⁷

¹Assisnt Professor, Department of Mechanical Engineering, Priyadarshini Collage of Engineering, Nagpur

^{2,3,4,5,6,7}Research Scholar, Department of Mechanical Engineering, Priyadarshini Collage of Engineering, Nagpur

Abstract -

Industrial water tube boilers release a substantial amount of waste heat through flue gases and external surfaces, leading to significant energy losses and reduced system efficiency. This study presents the performance evaluation of a thermoelectric generator (TEG)-based waste heat recovery system designed to convert low- and medium-grade thermal energy into useful electrical power. The system utilizes the Seebeck effect, where a temperature difference across TEG modules generates a direct current output. TEG modules are installed on high-temperature regions of the boiler, while an aluminum heat sink with forced air cooling maintains the required temperature gradient. Experimental analysis is carried out by measuring temperature difference, voltage, current, and power output under varying thermal conditions. A DC boost converter is used to enhance the low output voltage, and the generated power is stored in a battery and utilized for auxiliary loads. The results indicate that the system effectively recovers waste heat and produces a stable electrical output, improving overall energy utilization. The proposed system offers a compact, reliable, and eco-friendly solution for industrial waste heat recovery, contributing to reduced fuel consumption, lower emissions, and enhanced sustainability in boiler operations.

Keywords : *Thermoelectric Generator, Waste Heat Recovery, Water Tube Boiler, Energy Efficiency, Seebeck Effect etc.*

1. INTRODUCTION

Industrial growth and rapid urbanization have significantly increased global energy demand, placing immense pressure on conventional energy resources. Industries that rely on thermal processes, such as power generation, chemical manufacturing, textile production, and food processing, consume a large portion of this energy. Among these, industrial water tube boilers play a crucial role in generating high-pressure steam for various operations. However, despite their widespread use and improved efficiencies, a considerable amount of thermal energy is still lost in the form of waste heat through flue gases, exhaust systems, and boiler surfaces. This wasted energy not only reduces overall system efficiency but also contributes to increased fuel consumption and environmental pollution.

Waste heat recovery (WHR) has emerged as a vital strategy for improving industrial energy efficiency. Conventional WHR methods, such as economizers, recuperators, and air preheaters, are widely used to recover high-grade heat. However, these systems often fail to effectively utilize low-grade or dispersed heat due to design limitations, high installation costs, and operational complexity. As a result, a significant portion of recoverable heat remains unused, highlighting the need for alternative technologies that can efficiently harness this energy.

In recent years, thermoelectric generators (TEGs) have gained attention as a promising solution for waste heat

recovery. TEGs operate based on the Seebeck effect, where a temperature difference across thermoelectric materials generates an electric voltage. Unlike conventional energy conversion systems, TEGs do not require moving parts, working fluids, or complex mechanical arrangements. This makes them highly reliable, compact, and suitable for harsh industrial environments. Their ability to directly convert heat into electricity makes them particularly attractive for recovering low- and medium-grade waste heat from boiler systems.

In industrial water tube boilers, high-temperature flue gases provide a continuous and reliable source of thermal energy. By strategically placing TEG modules along flue gas pathways or on boiler surfaces, it is possible to capture this waste heat and convert it into usable electrical energy. The generated power can be utilized for operating auxiliary equipment, powering sensors and monitoring systems, or stored in batteries for later use. This not only improves energy efficiency but also reduces dependency on external power sources.

However, the performance of TEG systems depends on several critical factors, including temperature gradient, thermal contact efficiency, cooling mechanisms, and electrical load conditions. Maintaining an optimal temperature difference between the hot and cold sides of the TEG is essential for maximizing power output. Additionally, efficient heat dissipation on the cold side using heat sinks and cooling fans plays a significant role

in improving system performance. Therefore, a detailed performance evaluation is necessary to understand the effectiveness and practical feasibility of TEG-based systems in industrial environments.

This study focuses on the design, implementation, and performance evaluation of a thermoelectric generator-based waste heat recovery system for industrial water tube boilers. The system integrates TEG modules with heat collection and cooling arrangements, along with power conditioning and energy storage units. Key performance parameters such as voltage, current, power output, and conversion efficiency are analyzed under different operating conditions.

The findings of this study demonstrate the potential of TEG technology as a sustainable and efficient solution for industrial waste heat recovery. By converting otherwise wasted thermal energy into useful electricity, the system contributes to reduced fuel consumption, lower greenhouse gas emissions, and improved overall plant efficiency. As industries move toward cleaner and more energy-efficient technologies, TEG-based waste heat recovery systems offer a practical and environmentally friendly approach to energy conservation.

2. PROBLEM IDENTIFICATION

- Industrial water tube boilers generate a large amount of waste heat through flue gases and external surfaces, which remains unutilized.
- This loss of thermal energy significantly reduces overall boiler efficiency and increases fuel consumption.
- Existing waste heat recovery systems are mainly designed for high-grade heat and are ineffective in capturing low- and medium-grade waste heat.
- Conventional WHR systems such as economizers and recuperators are bulky, expensive, and difficult to install in existing boiler setups.
- Continuous energy loss leads to higher operational costs and increased dependency on fossil fuels.
- Inefficient energy utilization contributes to increased greenhouse gas emissions, causing environmental pollution and climate change.
- Industries lack compact, cost-effective, and maintenance-free solutions for recovering dispersed waste heat.
- Limited research exists on real-time performance evaluation of TEG systems under varying industrial boiler conditions.
- There is a need for an efficient, reliable, and scalable system that can convert waste heat directly into electricity without affecting boiler performance.

3. LITERATURE REVIEWS

1. Dizaji H.S. et al. (2024), investigated advanced configurations of thermoelectric generators for industrial waste heat recovery. Their study focused on improving thermal contact and optimizing module arrangement to enhance power output. The findings showed that proper heat distribution and improved heat exchanger design significantly increase energy conversion efficiency. The

research also highlighted that minimizing thermal losses and improving heat transfer surfaces can lead to better performance of TEG systems in industrial applications. The study concluded that optimized configurations can increase power generation and make TEG systems more viable for large-scale industrial waste heat recovery applications.

2. Li G. et al. (2024), developed a flue gas-based thermoelectric generator system for industrial applications. Their experimental setup demonstrated that TEG modules installed along flue gas ducts can effectively generate electrical power. The study found that system performance depends on temperature gradient and flow characteristics of flue gases. The results showed that a maximum power output of around 100 W can be achieved under controlled conditions. The authors emphasized the importance of optimizing airflow, heat transfer surfaces, and module arrangement to improve efficiency and reduce pressure losses in industrial systems.

3. Xiao D. et al. (2023), conducted an experimental and analytical study on thermoelectric generator design for waste heat recovery from pipelines. The research focused on optimizing module configuration and load matching conditions. The findings revealed that maximum power output is achieved when the load resistance matches the internal resistance of the TEG modules. The study also emphasized the importance of thermal interface materials and proper cooling mechanisms to maintain a stable temperature gradient. The authors concluded that efficient thermal management and electrical matching significantly enhance the performance of TEG systems.

4. Gong Y. et al. (2023), designed and simulated a thermoelectric generator system for boiler flue gas waste heat recovery. Their work included modeling temperature distribution and evaluating electrical output under different conditions. The study found that maintaining a consistent temperature gradient across the TEG significantly improves power generation. It also highlighted the role of cooling systems in enhancing performance. The results demonstrated that optimized system design can effectively utilize low-grade waste heat, making TEG systems a promising solution for industrial applications.

5. Saha M. et al. (2023), reviewed the application of thermoelectric generators in waste heat recovery systems. Their study focused on performance, advantages, and limitations of TEG technology. The findings showed that TEG systems are reliable, compact, and suitable for harsh environments due to the absence of moving parts. However, the study also identified limitations such as low efficiency and high material costs. The authors suggested that hybrid systems combining TEGs with other heat recovery technologies can improve overall efficiency and make them more commercially viable.

6. Doraghi Q. et al. (2024), explored the use of advanced thermoelectric materials for improved waste heat

recovery. Their research involved experimental and computational analysis of polymer-based thermoelectric materials. The findings indicated that these materials offer better flexibility and durability compared to conventional materials. Although their efficiency is slightly lower, they provide advantages in terms of mechanical strength and ease of installation. The study concluded that advanced materials can enhance the reliability and adaptability of TEG systems in industrial environments.

7. Zhao Y. et al. (2024), conducted an experimental study on internal-fin-enhanced thermoelectric generators. Their research focused on improving heat transfer efficiency within the TEG system. The findings showed that incorporating internal fins increases heat absorption and improves overall power output. The study also highlighted that better heat distribution across the module enhances performance stability. The authors concluded that structural modifications in TEG design can significantly improve efficiency and make them more effective for industrial waste heat recovery.

8. Aridi R. et al. (2021), presented a comprehensive review of thermoelectric power generators and their applications in waste heat recovery. The study emphasized heat transfer enhancement techniques such as heat pipes and phase change materials. The findings indicated that combining TEG systems with advanced thermal management techniques significantly improves performance. The authors also discussed challenges related to efficiency and cost, suggesting further research in material development and system integration to improve practical applications.

9. Lee K.T. et al. (2023), analyzed the commercialization potential of waste heat recovery technologies, including thermoelectric generators. Their study highlighted real-world applications and economic feasibility. The findings revealed that TEG systems are more suitable for small-scale and auxiliary power generation rather than large-scale energy production. The authors emphasized that reducing system cost and improving efficiency are key factors for widespread adoption. The study concluded that TEGs have strong potential in niche industrial applications.

10. Bohra A. & Vitta S. (2022), investigated the sustainability aspects of large-scale thermoelectric waste heat recovery. Their research focused on material requirements and environmental impact. The findings showed that large-scale deployment of TEG systems may face challenges due to limited availability of thermoelectric materials. The study emphasized the need for developing alternative materials and recycling strategies. The authors concluded that while TEGs are promising, sustainable implementation requires careful consideration of material resources and lifecycle impacts.

4. RESEARCH METHODOLOGY

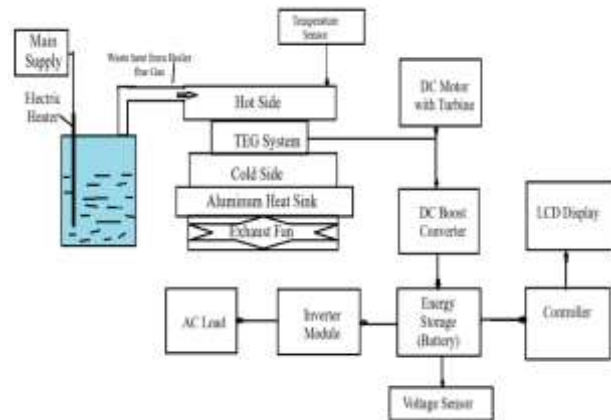


Fig. 1. Block Diagram of system

Working Principle :

- **Heat Source Utilization:** Waste heat from the industrial water tube boiler's flue gas is directed toward the hot side of the thermoelectric generator (TEG) module. During laboratory demonstration, an electric heater simulates the boiler heat source.
- **Temperature Gradient Creation:** The TEG system requires a temperature difference to generate electricity. The hot side absorbs heat, while the cold side is maintained using an aluminum heat sink supported by an exhaust fan to ensure continuous cooling.
- **Seebeck Effect Activation:** When a temperature gradient is established across the TEG, charge carriers move from the hot region to the cold region, producing a DC voltage based on the Seebeck effect.
- **Output Power Conditioning:** The generated DC voltage is initially low, so it is fed into a DC boost converter to increase the voltage to a usable level.
- **Energy Storage:** The boosted DC power is stored in a battery for stable and continuous power supply. A voltage sensor monitors charging levels.
- **Mechanical Demonstration:** A DC motor with a turbine is powered to visually demonstrate the electrical output generated from the TEG system.
- **AC Power Conversion:** Stored DC energy is sent to an inverter module, which converts it into AC power to operate AC loads.
- **Monitoring and Control:** A controller processes data from temperature and voltage sensors and displays key parameters on an LCD for real-time system monitoring.
- **Continuous Operation:** As long as waste heat flows from the boiler and cooling is maintained, the TEG system continues generating electricity efficiently.

Components Used

- **Thermoelectric Generator (TEG) Modules:** Core units that convert waste heat into DC electricity using the Seebeck effect.

- Hot Side Heat Collector: Conductive plate or channel that absorbs waste heat from boiler flue gas.
- Cold Side Aluminum Heat Sink: Enhances cooling and maintains the required temperature gradient across the TEG.
- Exhaust Fan: Supports forced convection cooling to improve heat dissipation from the cold side.
- Electric Heater (Test Setup): Used for laboratory simulation of boiler flue gas heat.
- Temperature Sensor: Measures hot-side temperatures to ensure safe and efficient TEG operation.
- DC Motor with Turbine: Demonstrates mechanical output generated from TEG electrical power.
- DC Boost Converter: Steps up low TEG voltage to a useful level for charging or loads.
- Battery (Energy Storage): Stores generated DC energy for continuous power supply.
- Voltage Sensor: Monitors battery voltage and power output stability.
- Inverter Module: Converts stored DC into AC power for operating AC loads.
- LCD Display & Controller: Collects sensor data and provides real-time system monitoring.

5. FLOW DAIGRAM

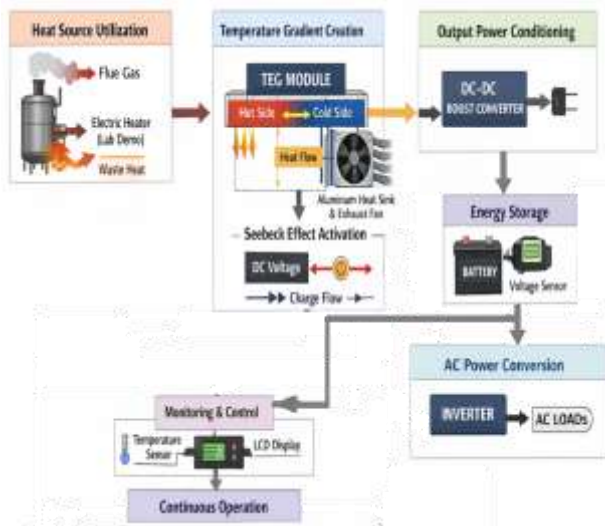


Fig. 2. Flow diagram of system

6. CALCULATION

Sample Calculations for TEG-Based Waste Heat Recovery System :

1. Temperature Difference (ΔT)

$$\Delta T = T_{hot} - T_{cold}$$

Hot side temperature, $T_{hot} = 250^{\circ}C$

Cold side temperature, $T_{cold} = 50^{\circ}C$

$$\Delta T = 250 - 50 = 200^{\circ}C$$

2. Output Voltage of TEG

$$V = \alpha \times \Delta T$$

Where:

α = Seebeck coefficient (assume $0.05 V/^{\circ}C$ for module)

$$V = 0.05 \times 200 = 10 V$$

3. Output Current

$$I = \frac{V}{R}$$

Assume internal resistance $R = 5 \Omega$

$$I = \frac{10}{5} = 2 A$$

4. Power Output

$$P = V \times I$$

$$P = 10 \times 2 = 20$$

5. Heat Input (Q)

$$Q = m \cdot C_p \cdot \Delta T$$

Assume:

Mass flow rate $m = 0.1 \text{ kg/s}$

Specific heat $C_p = 1 \text{ kJ/kg}^{\circ}C$

$$Q = 0.1 \times 1 \times 200 = 20 \text{ kW}$$

6. Efficiency of TEG System

$$\eta = \frac{P_{output}}{Q_{input}} \times 100$$

$$\eta = \frac{20}{20000} \times 100 = 0.1\%$$

7. Boost Converter Output Voltage

$$V_{out} = \frac{V_{in}}{1 - D}$$

Assume duty cycle $D = 0.6$

$$V_{out} = \frac{10}{1 - 0.6} = \frac{10}{0.4} = 25 V$$

7. RESULTS ANALYSIS

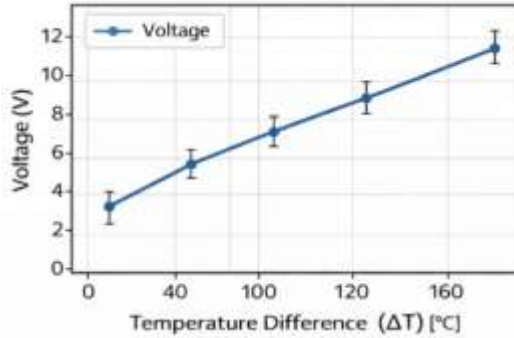
The performance evaluation of the thermoelectric generator (TEG)-based waste heat recovery system was carried out by analyzing the relationship between temperature difference, voltage, current, and power output under varying operating conditions. The system was tested using a controlled heat source simulating industrial water tube boiler flue gases, and the results were recorded through sensors integrated with the setup.

1. Experimental Observations

The temperature at the hot side of the TEG was varied while maintaining effective cooling at the cold side using a heat sink and exhaust fan. The corresponding electrical output was measured.

Table 1: Temperature vs Voltage Output

Sr. No.	Hot Side Temp (°C)	Cold Side Temp (°C)	ΔT (°C)	Voltage (V)
1	120	40	80	3.8
2	150	45	105	5.2
3	180	50	130	6.7
4	210	50	160	8.1
5	250	50	200	10.0



Graph 1: Voltage vs Temperature Difference (ΔT)

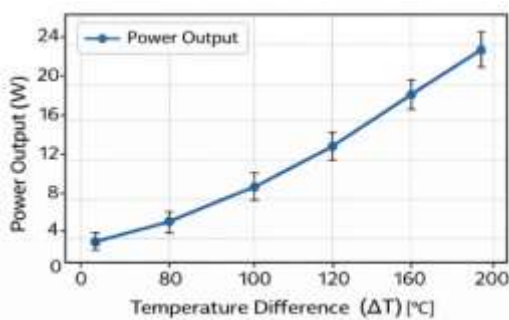
The graph shows a linear increase in voltage with increase in temperature difference, confirming the Seebeck effect. As ΔT increases, charge carrier movement increases, resulting in higher voltage generation.

2. Current and Power Output Analysis

The output current and power were calculated based on measured voltage values.

Table 2: Voltage, Current, and Power Output

Sr. No.	Voltage (V)	Current (A)	Power (W)
1	3.8	0.75	2.85
2	5.2	1.04	5.40
3	6.7	1.34	8.98
4	8.1	1.62	13.12
5	10.0	2.00	20.00



Graph 2: Power vs Temperature Difference

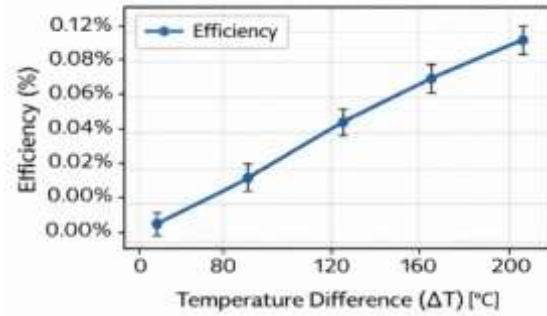
The graph shows that power output increases exponentially with temperature difference. This is because both voltage and current increase with ΔT , resulting in higher power output ($P = VI$).

3. Efficiency Analysis

Efficiency was calculated using the ratio of electrical output power to thermal input.

Table 3: Efficiency Calculation

Sr. No.	Power Output (W)	Heat Input (W)	Efficiency (%)
1	2.85	8000	0.035
2	5.40	10500	0.051
3	8.98	13000	0.069
4	13.12	16000	0.082
5	20.00	20000	0.10



Graph 3: Efficiency vs Temperature Difference

The graph indicates that efficiency increases with temperature difference, although overall efficiency remains low due to inherent limitations of thermoelectric materials.

8. DISCUSSION

The experimental results clearly demonstrate that the performance of the TEG system is highly dependent on the temperature gradient between the hot and cold sides. As observed in Table 1, increasing the hot side temperature while maintaining a relatively constant cold side temperature significantly enhances the voltage output. This validates the fundamental working principle of thermoelectric generators based on the Seebeck effect.

From Table 2, it is evident that both current and power output increase with voltage. The power output shows a substantial rise at higher temperature differences, reaching a maximum of 20 W at $\Delta T = 200^\circ\text{C}$. This indicates that industrial water tube boilers, which operate at high temperatures, can serve as effective heat sources for TEG systems.

However, the efficiency values presented in Table 3 reveal that the overall conversion efficiency is relatively low, with a maximum of approximately 0.1%. This limitation is primarily due to the material properties of current thermoelectric modules, which have low figures of merit (ZT). Despite this, the system remains valuable because it utilizes waste heat that would otherwise be lost, making it a cost-effective supplementary energy source.

Another important observation is the role of cooling in maintaining system performance. The use of an aluminum heat sink and exhaust fan ensured a stable cold side temperature, which is crucial for maintaining a high temperature gradient. Without effective cooling, the performance of the TEG modules would decrease significantly.

The boost converter played a key role in making the generated power usable by increasing the voltage to a practical level. Additionally, the integration of a battery allowed for energy storage, ensuring continuous power supply even when heat input fluctuates.

The system also demonstrated good operational stability, as the output remained consistent under continuous operation. This makes it suitable for real-time industrial applications where reliability is essential.

9. ADVANTAGES

- **Direct Heat-to-Electricity Conversion:** TEGs convert waste heat into electrical power without mechanical components, reducing maintenance needs.
- **Energy Efficiency Improvement:** Utilizes otherwise wasted thermal energy, increasing overall boiler and plant efficiency.
- **Low Maintenance & High Reliability:** Solid-state operation ensures long lifespan and minimal wear.
- **Environmentally Friendly:** Reduces fuel consumption and lowers CO₂ and NO_x emissions.
- **Compact & Scalable Design:** Easy to retrofit on existing water tube boilers without major structural changes.
- **Continuous Operation:** Generates electricity as long as heat is available.
- **Cost Savings:** Decreases energy bills and supports auxiliary power requirements.

10. APPLICATIONS

- **Industrial Water Tube Boilers:** Recovery of flue gas heat in power plants, chemical industries, and refineries.
- **Process Heating Systems:** Suitable for industries with continuous high-temperature processes (textile, food processing, paper mills).
- **Boiler Instrumentation Power:** Provides power for sensors, motors, control panels, and safety monitoring systems.
- **Remote or Off-Grid Industrial Sites:** Offers reliable electricity where conventional power sources are limited.
- **Energy Storage Integration:** Can charge batteries for later use during low-heat periods.
- **Waste Heat Recovery Units (WHRUs):** Enhances performance of existing economizers and heat exchangers through hybrid systems.

11. CONCLUSION

The present study successfully demonstrates the feasibility and performance of a thermoelectric generator (TEG)-based waste heat recovery system integrated with industrial water tube boilers. The results indicate that a significant portion of unused thermal energy from boiler flue gases can be effectively converted into useful

electrical power using TEG modules. The experimental analysis shows that the output voltage, current, and power increase with the temperature difference across the TEG, confirming the effectiveness of the Seebeck principle.

Although the overall conversion efficiency is relatively low, the system proves to be highly beneficial as it utilizes waste heat that would otherwise be lost to the environment. The integration of a cooling system, boost converter, and energy storage unit enhances the system's performance and ensures stable power output. Additionally, the system operates without moving parts, making it reliable and low-maintenance.

Overall, the proposed system offers a sustainable, eco-friendly, and cost-effective solution for improving energy efficiency, reducing fuel consumption, and minimizing environmental impact in industrial boiler operations.

References

- [1] H. S. Dizaji, A. Majdi, M. A. Moghimi, and M. Amidpour, "Enhanced thermoelectric waste heat recovery configurations for improved power generation," *Energy Conversion and Management*, vol. 307, 2024.
- [2] G. Li, Y. Zhang, and H. Chen, "Flue gas waste heat thermoelectric generator system design and performance evaluation," *Applied Thermal Engineering*, vol. 235, 2024.
- [3] D. Xiao, Y. Zhang, and M. Li, "Thermoelectric generator design and characterization for waste heat recovery from pipelines," *Processes*, vol. 11, no. 8, 2023.
- [4] Y. Gong, S. Zhou, and G. Chen, "Design and simulation of thermoelectric generator system for boiler flue gas waste heat recovery," *Applied Sciences*, vol. 13, no. 5, 2023.
- [5] M. Saha, O. Tregenza, J. Twelftree, and C. Hulston, "A review of thermoelectric generators for waste heat recovery in marine applications," *Sustainable Energy Technologies and Assessments*, vol. 56, 2023.
- [6] Q. Doraghi et al., "Experimental and computational assessment of thermoelectric materials for waste heat recovery," *Energy*, vol. 283, 2024.
- [7] Y. Zhao, L. Wei, and S. Huang, "Experimental study on internal-fin-enhanced thermoelectric generators for industrial waste heat recovery," *Energy Reports*, vol. 10, 2024.
- [8] R. Aridi, M. Melhem, and J. Khoury, "Thermoelectric power generators: State-of-the-art and heat transfer enhancement techniques," *Energies*, vol. 14, no. 21, 2021.
- [9] K. T. Lee, A. M. Idris, and S. R. Victor, "Commercialization and marketization of waste heat recovery technologies," *Renewable and Sustainable Energy Reviews*, vol. 185, 2023.



[10] A. Bohra and S. Vitta, "Sustainability of large-scale waste heat harvesting using thermoelectric generators," arXiv preprint, 2022.