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Converting Waste Heat into Usable Electrical Energy Using Thermoelectric Generator

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ABSTRACT

This study explores the performance of thermoelectric generators (TEGs) in converting waste heat into usable electrical energy under different thermal conditions. Three experimental configurations were evaluated: (1) a candle with ice cubes for cooling, (2) a candle with a fan, and (3) car exhaust with ambient air cooling. The candle–ice setup achieved the highest initial voltage output of approximately 2.38 V, attributed to the large temperature difference between the heat source and cooling surface; however, the voltage decreased gradually as the ice melted. The candle–fan setup produced a stable voltage in the range of 1.8–2.0 V, with continuous airflow maintaining a moderate but steady temperature gradient. The car exhaust–ambient air configuration generated the lowest output, between 1.2 and 1.5 V, but required no additional energy for cooling, making it the most practical for real-world applications. The results indicate that while high initial temperature differences yield greater peak voltages, sustaining a consistent gradient is more crucial for continuous power generation. These findings highlight the potential of simple, low-cost TEG systems for small-scale, off-grid, and passive energy recovery applications, such as in vehicles, rural cookstoves, or industrial exhaust systems, offering a clean, silent, and sustainable means of utilizing otherwise wasted heat.

Keywords: Thermoelectric Generator (Teg), Waste Heat Recovery, Temperature Gradient, Cooling Efficiency, Voltage Output

1. Introduction

The increasing global demand for energy underscores the need for sustainable and efficient alternatives that reduce dependence on fossil fuels and limit greenhouse gas emissions. One promising avenue is the recovery of waste heat—thermal energy that is generated but not utilized in processes such as power generation, manufacturing, transportation, and domestic heating. At present, much of this heat escapes into the environment, representing a substantial loss of potential energy. Converting this untapped resource into electrical power offers a practical means of improving overall efficiency, lowering operational costs, and contributing to environmental protection. Waste heat is available across a broad temperature spectrum, from high-temperature industrial processes like steelmaking and cement production to lower-temperature sources such as vehicle exhausts and household heating systems. Despite being widely available, it remains underutilized, and comprehensive data on its recoverable potential is limited. Harnessing this resource could play a key role in advancing clean energy adoption, supporting climate goals, and strengthening the resilience of modern energy systems [1]. Waste heat recovery is all about making use otherwise be lost from industrial processes, power generation, and other activities, helping to boost efficiency and cut down on emissions. There are several ways to do this. Heat exchangers can capture heat from exhaust gases or liquids and put it back to work, while regenerative burners reuse combustion heat to warm incoming air. Waste heat boilers turn hot exhaust into steam, and thermoelectric generators (TEGs) can directly turn heat into electricity. Organic Rankine Cycle (ORC) systems make use of low-grade heat to produce power, and absorption chillers can use waste heat for cooling. Heat can be harvested and recovered using thermoelectric (TE) technology, which is considered an environmentally acceptable alternative. Thermoelectric generators (TEG) turn the heat directly into electrical energy [2].

2. Literature review

Early studies focused on discovering and developing thermoelectric materials with improved performance and efficiency. Researchers have examined a range of candidates, including half-Heusler compounds, skutterudites, and bismuth telluride, each showing significant potential under different conditions. Many publications also report findings on heat transfer rates, thermal stability, and pressure drop in both thermoelectric materials and associated heat exchangers. The main findings were as follows: Low electric resistance and high thermal resistance semiconductors generate the power of a TEG; the greater the temperature differential between the heat source and heat sink, the higher the TEG's power [3]. The field of thermoelectric has seen significant gains in enhancing thermoelectric characteristics due to the recently gained ability to make nanostructured materials [4]. The

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development of nanostructured materials with exceptional thermoelectric qualities that greatly outperform those of conventional materials has been made possible by this cutting-edge field. Improving the figure of merit (ZT), which measures a material's efficiency in generating electricity from heat, is the main goal of these developments. ZT values have significantly improved in nanostructured materials, including superlattices, nanowires, and quantum dots. These materials increase electrical conductivity and decrease thermal conductivity, among other methods, to reach higher ZT values. One crucial area of research has been the incorporation of nanostructured thermoelectric materials into current systems. The thermoelectric performance of materials greatly depends on the synthesis technique used, as different methods influence the structure and efficiency of the material. A dimensionless metric is used to assess how well thermoelectric materials operate. It is defined as –

$$ZT = (S^2 \times \sigma \times T) / k \quad (1)$$

T is the absolute temperature at which the parameters are measured, s is the electrical conductivity, k is the thermal conductivity, and S is the Seebeck coefficient, which was previously defined [4]. ZT should be as high as possible for a material to be an effective thermoelectric material [8] Unfortunately, there aren't many materials with these qualities found in nature [4]. The efficiency of thermoelectric materials is commonly evaluated using the dimensionless figure of merit (ZT), which varies with temperature and material type. Table 1 presents ZT values for different thermoelectric materials across various temperature ranges. Table 1 presents ZT values for different thermoelectric materials across various temperature ranges. These ongoing advancements highlight the importance of materials science in unlocking the full potential of thermoelectric technology. By optimizing both the structural and electrical properties of these materials, researchers can move closer to achieving commercially viable solutions for large-scale waste heat recovery.

Table 1. ZT values for various material types at various temperatures.

Material	Type	ZT Value	Temperature	Ref
PbSeTe	n-type	3	550 K	[5]
GdPdBi		0.085	615 K	[6]
SiGe	P-type	0.6–1.0	973–1173 K	[7]
TeAgGeSb	p-type	1.2	423–573 K	[7]
PbTe–SrTe	p-type	1.7	~800 K	[7]
LdPdBi		0.084	496 K	[6]
LaTe	p-type	0.4	973–1173 K	[7]

3. Research methodology

The study combines computational modeling, experimental synthesis, and characterization to improve thermoelectric (TE) materials for waste heat recovery. Material selection, performance prediction, and validation are integrated with sustainability and economic assessments to optimize high-performance TE materials.

3.1 Assumptions

This study is built on a set of clear assumptions that shaped the experiments, analysis, and overall approach to improving thermoelectric (TE) materials for waste heat recovery. First, the precursor materials are assumed to be of very high purity, so that impurities have little to no impact on TE properties. The synthesized components are expected to have a uniform composition and structure, ensuring consistency in performance. It is also assumed that synthesis methods—such as solid-state reactions, spark plasma sintering, and additive manufacturing—produce reliable and repeatable results across different batches. The TE properties of the materials should remain stable during testing, with any changes falling within acceptable limits. To maintain credibility, all characterization techniques, including XRD, SEM, TEM, Seebeck measurements, and conductivity tests, are considered well-calibrated and dependable. Testing conditions, such as temperature and environmental factors, are designed to reflect realistic, real-world scenarios. Additionally, the chosen synthesis processes are assumed to be scalable without major losses in performance, and the materials should be easy to integrate into existing waste heat recovery systems. Finally, sustainability is a key consideration, with environmental impact assessments reflecting the entire life cycle of the material, from production to end use.

3.2 Materials and Methods

The materials and equipment used for synthesizing, characterizing, and testing thermoelectric (TE) materials for waste heat recovery are mentioned below. The aim is to systematically develop and refine TE materials to enhance performance and applicability.

TEG Modules – Commercial Bi_2Te_3-based modules suitable for low-temperature waste heat recovery.

Heat Sources – Candle flame for controlled lab heating and vehicle exhaust gas for real-world simulation.

Cooling Systems – Ice cubes on an aluminum plate (passive cooling), a fan for forced convection, and ambient air for natural convection during outdoor tests.

Heat Sinks – Aluminum heat sinks on the cold side to improve heat dissipation.

Measuring Instruments – Voltmeter/multimeter for output voltage readings.

Supporting Equipment – Stands and clamps for positioning, metal plates for heat transfer, and thermal paste to minimize thermal resistance.

3.3 Experimental setup

Experiment 1: Candle Flame as Heat Source & Ice Cube as Cooling

1. A TEG module was placed between a metal plate heated by a candle flame below and a flat aluminum plate with ice cubes on top.
2. Thermal paste was applied between all interfaces to enhance heat transfer.
3. The setup was stabilized using clamps and insulation to minimize heat loss.
4. As heat transferred from the candle to the hot side and cooling occurred on the top with ice, a temperature gradient developed.
5. Voltage output was measured using a digital multimeter.
6. This setup generated a peak voltage of 2.38 volts, sufficient to light up a small LED.

Experiment 2: Candle Flame as Heat Source & Fan Cooling

1. A similar setup was maintained as in Experiment 1, but instead of ice, a fan was directed toward the cold side of the TEG module.
2. The fan enhanced air circulation and improved convective heat transfer from the heat sink.
3. Temperature difference was maintained for a stable output.
4. Voltage readings were taken at intervals using the multimeter.
5. This setup produced slightly lower voltage than the ice-cooling method but maintained consistent output over time.

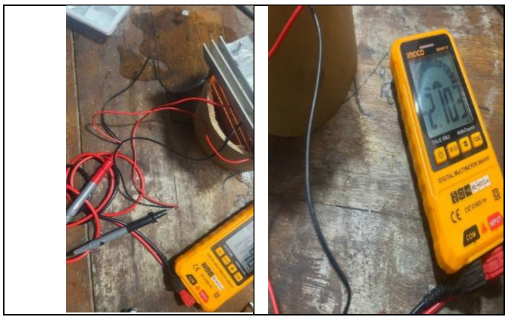

Fig. 1. Candle as heat source with ice cubes for cooling

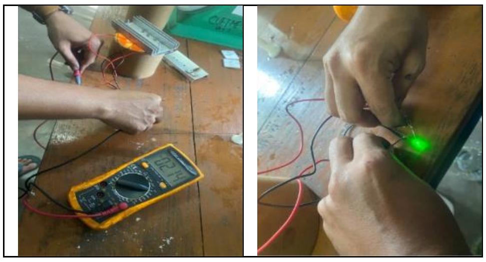

Fig. 2. Candle as heat source with a fan as cooling method

Experiment 3: Car Exhaust Gas as Heat Source & Ambient Air as Cooling

1. The TEG module was mounted on the exhaust pipe of a running vehicle, with a metal plate in between to distribute the heat evenly.
2. The cold side was left exposed to natural ambient air to simulate a passive outdoor cooling environment.
3. No external cooling was applied; the setup relied on natural convection.
4. Voltage was recorded after the engine reached operating temperature.
5. The voltage output ranged between 1.2 to 1.5 volts, depending on exhaust gas temperature and ambient air conditions.

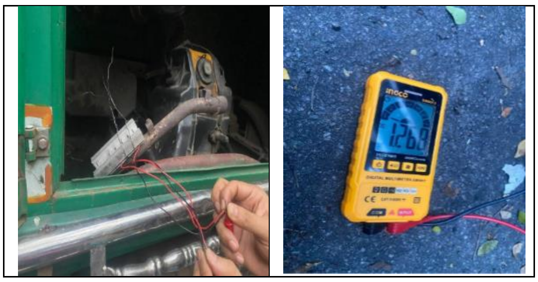

Fig. 3. Car exhaust as heat source with ambient air cooling

3.4 Analysis

This section presents the evaluation of how the thermoelectric generator (TEG) system performed under three distinct thermal conditions. Each setup used a different combination of heat source and cooling method. The goal was to compare voltage outputs, identify performance trends, and understand which setup offered better energy conversion potential in practical situations.

3.4.1 Setup: Candle with Ice Cube Cooling

In this arrangement, the candle provided consistent heating from below, while ice cubes on top created a strong cooling effect. This setup produced the largest temperature difference across the TEG.

- The maximum voltage recorded was 2.38 volts.
- The voltage was high enough to power a small LED during the test.
- The output remained stable until the ice melted significantly, reducing the cooling efficiency.

Takeaway: This setup achieved the highest efficiency among all three, showing that a strong temperature contrast is key to improving TEG output. However, it may not be ideal for continuous use due to the temporary nature of the cooling source.

3.4.2 Setup: Candle with Fan Cooling

Here, the same heat source (candle) was paired with a fan to cool the cold side using forced air. Although the cooling effect was not as strong as the ice setup, it remained consistent over time.

- Voltage output was slightly lower than the ice-cooled version, staying below 2 volts.
- The system remained operational longer, as the fan could continuously supply airflow.

Takeaway: While the voltage was not the highest, the fan-based cooling method offered better long-term stability and practicality, especially for repeated or extended tests.

3.4.3 Setup: Exhaust Gas with Ambient Air

This experiment aimed to test the TEG in a real-world scenario, using the heat from a running vehicle's exhaust. The cooling depended entirely on natural airflow from the environment.

- Voltage ranged from 1.2 to 1.5 volts, depending on factors like exhaust temperature and surrounding air conditions.
- The system delivered steady performance, though the voltage was less than the other two setups.

3.4.4 Performance Comparison of Different Experimental Setups

This table 2 compares different experimental setups used for generating electricity through thermoelectric generators. It highlights how varying heat sources and cooling methods influence the maximum voltage output and the stability of the system. Each setup offers distinct advantages and challenges in terms of performance and reliability. Some configurations produce higher voltage but may have shorter operational life, while others provide steadier output over time. The table also notes practical considerations such as ease of reuse and real-world applicability. This comparison provides valuable insight into optimizing thermoelectric generator designs based on specific energy harvesting needs and conditions. Understanding these factors is essential for improving the efficiency and durability of TEG systems.

Setup 1, using a candle and ice cube, produced the highest maximum voltage of 2.38 V but showed medium stability and was short-lived. Setup 2 combined a candle with a fan, yielding a voltage between 1.8 and 2.0 V, with high stability and steady output. Setup 3 used car exhaust and ambient air, resulting in a voltage range of 1.2 to 1.5 V and medium stability, representing a real-world application with lower voltage output. These results highlight the balance between voltage output and system stability in different configurations. Furthermore, the analysis indicates that while maximizing voltage is beneficial, ensuring consistent performance over time is equally important for practical use. The choice of setup should therefore consider the intended application, operational environment, and available cooling methods to achieve optimal efficiency and reliability.

Table 2. Comparison of three thermoelectric generator setups with different heat sources and cooling methods

Setup No.	Heat Source	Cooling Method	Max Voltage (V)	Stability (High/Med/Low)
1	Candle	Ice Cube	2.38	Medium
2	Candle	Fan	~1.8 – 2.0	High
3	Car Exhaust	Ambient Air	1.2 – 1.5	Medium

3.5 Comparison

The three TEG setups were compared in terms of voltage output, stability, cooling efficiency, and practical application.

Voltage Output – Ice cooling (Setup 1) achieved the highest peak voltage due to its large temperature gradient. Fan cooling (Setup 2) produced slightly lower voltage but more consistent results. Exhaust with ambient air (Setup 3) generated the lowest voltage but reflected realistic conditions.

Stability – The fan-cooled setup was the most stable. Ice-cooled output dropped quickly as melting began, while exhaust-based output fluctuated with engine and weather changes.

Cooling Efficiency – Ice offered the strongest cooling but only briefly. The fan provided steady cooling over longer periods, while ambient air required no equipment but was least effective.

Application Potential – Setup 1 suits short-term or emergency use, Setup 2 works for controlled continuous operation, and Setup 3 is most practical for real-world waste heat recovery without extra cooling systems.

After six minutes, in all three setups, the voltage dropped over time mainly due to the **reduction in temperature difference (ΔT)** across the thermoelectric module. In the **candle–ice setup**, melting ice reduced cooling efficiency, narrowing the gradient; in the **candle–fan setup**, heat buildup and limited airflow caused gradual thermal balance; and in the **car exhaust–air setup**, fluctuating exhaust temperature and weak natural cooling lowered ΔT. As the thermal gradient weakened, the generated voltage decreased steadily in each case.

4. Data Collection and Analysis

All experiments were performed under controlled indoor and outdoor conditions to evaluate thermoelectric performance using different cooling strategies. The indoor setups (candle + ice, candle + fan) were conducted at 28–32 °C, while the outdoor test (exhaust + air) took place at 30–35 °C. Each configuration used the same Bi_2Te_3-based TEG module positioned between aluminum plates with thermal paste to ensure uniform heat transfer and minimal losses.

Table 3: Comparison of three TEG setups based on voltage output, stability, cooling efficiency, and practical application.

Time (min)	Candle +Ice (V)	Candle+ Fan (V)	Exhaust + Air (V)
0	0.0	0.0	0.0
0.5	1.8	1.0	0.6
1	2.2	1.5	1.0
2	2.38	1.8	1.3
3	2.30	1.9	1.4
4	2.10	2.0	1.5
5	1.90	2.0	1.4
6	1.70	1.95	1.3
7	1.50	1.90	1.3
8	1.30	1.85	1.2
9	1.10	1.80	1.2
10	0.90	1.80	1.2

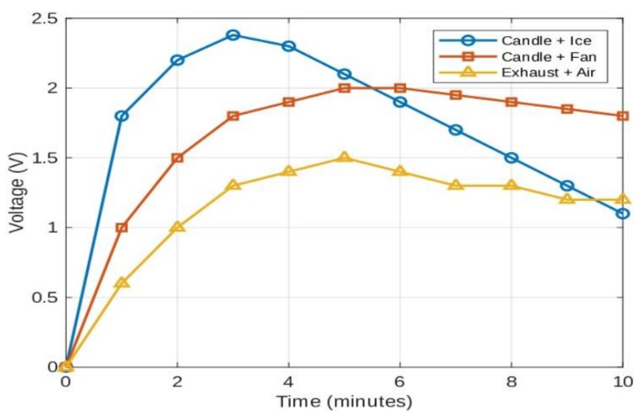

Fig. 4. Voltage Response of Thermoelectric Generator Under Varying Thermal Conditions.

A calibrated digital multimeter (±0.01 V accuracy) recorded voltage every 30 seconds for 5–10 minutes after the system reached thermal steady state. Each experiment was repeated three times, and the mean values were taken to minimize random error. The estimated heat-source temperatures were approximately 600–900 °C for the candle flame and 200–400 °C for the vehicle exhaust. Minor uncertainties arose from melting of ice, flame instability, and ambient fluctuations; however, these did not significantly affect the overall performance trends.

5. Results and Discussion

The results reveal clear differences in voltage behavior and operational stability across the three configurations.

Candle + Ice: Generated the highest initial voltage, approximately 2.38 V, because of the large temperature difference between the hot and cold sides. However, once the ice melted, the cooling capacity dropped sharply, causing a rapid voltage decline after about six minutes.

Candle + Fan: Produced a slightly lower voltage, in the range of 1.8–2.0 V, yet maintained far greater stability since

forced convection continuously removed heat from the cold side. This steady performance highlights the importance of sustaining, rather than maximizing, the temperature gradient.
Exhaust + Air: Delivered a voltage between 1.2 and 1.5 V once the exhaust pipe reached its normal operating temperature. Although the output was the lowest, the setup required no auxiliary energy for cooling, proving effective for continuous waste-heat recovery in real environments.
The voltage drop after several minutes is directly linked to the reduction in temperature difference (ΔT) across the TEG. As the ice melted, thermal resistance on the cold side increased, reducing ΔT and thus the Seebeck voltage. Similarly, in the fan setup, convective heat transfer reached steady state, stabilizing voltage output. This agrees with Twaha et al. (2016), who highlighted that the Seebeck voltage is proportional to ΔT and the material's thermoelectric coefficient.

5.1 Practical Implications

These findings highlight how thermoelectric generators (TEGs) can transform low-grade waste heat into practical, usable electricity across a wide range of applications. In the automotive sector, TEGs can be installed near exhaust pipes to charge batteries or power sensors without consuming extra fuel. In industrial settings, they can capture heat from boilers, chimneys, or hot pipes, allowing that energy to be reused or used to power equipment. In space exploration, NASA's radioisotope thermoelectric generators (RTGs) operate on the same principle, supplying dependable power for long-duration space probes. For off-grid communities, TEGs can be attached to biomass stoves to charge phones, power lights, or run radios, providing a simple energy solution in remote areas. Even in personal technology, they can harvest body heat to run small electronics like watches or fitness trackers. Because they are silent, durable, and highly adaptable, TEGs are well-suited for both everyday applications and extreme environments.
In Bangladesh, where many small industries and rural households face limited or inefficient energy access, thermoelectric modules can capture waste heat from sources like cookstoves, chimneys, and vehicle exhausts to generate electricity for low-power devices such as LED lights or sensors. This approach supports decentralized energy use, improves efficiency, reduces costs, and aligns with national renewable energy goals.

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