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Conversion of Heat Absorbed (Waste Heat) in a Building for Electricity Generation Using a Thermoelectric Generator

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Abstract

This study investigates the feasibility of thermoelectric generators (TEGs) for recovering waste heat from building systems and converting it into electrical energy through the Seebeck effect. A journal-scale simulation framework integrating ANSYS thermal modeling with MATLAB/Simulink electrical analysis was developed to evaluate TEG deployment on building envelope surfaces at the Federal Polytechnic Nyak Shendam, Nigeria. Results demonstrate a proportional increase in electrical output with rising temperature gradients, confirming predictable thermoelectric performance under practical environmental conditions. Roof and wall installations exhibited the highest recovery potential, producing approximately 3–15 W per module depending on thermal differentials and operating parameters. Model validation showed strong agreement between simulation platforms, with deviations remaining below 6%, indicating reliable predictive capability for engineering design and optimization. Parametric studies further identified optimal electrical load resistance, module arrangement, and surface placement strategies to maximize conversion efficiency and power stability. Techno-economic analysis revealed a feasible investment profile, including an estimated payback period of seven years, a net present value of USD 2,150, and an internal rate of return of 15%, supporting long-term deployment potential in institutional buildings. Environmental impact assessment projected annual electricity savings of 7,096 kWh alongside a reduction of approximately 6.03 tons of carbon dioxide emissions, demonstrating measurable sustainability benefits. Overall, the findings confirm that TEG-based waste heat recovery offers a technically viable, economically practical, and environmentally sustainable solution for decentralized, low-power building energy systems in developing regions. The proposed framework also supports scalable retrofitting strategies, enabling integration with existing infrastructure while maintaining minimal maintenance requirements over time.

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INTRODUCTION

The rapid growth of urbanization and the continuous expansion of modern infrastructure have led to a substantial increase in global energy demand, with buildings emerging as one of the largest consumers of energy worldwide [1]. Residential, commercial, and institutional buildings collectively account for a significant share of electricity usage due to heating, ventilation and air-conditioning (HVAC) systems, lighting, electronic devices, and other auxiliary services [2]. A considerable portion of this consumed energy is not effectively utilized but is instead dissipated into the environment in the form of waste heat [3]. This loss of thermal energy represents a critical inefficiency in building energy systems and highlights the urgent need for innovative approaches to energy recovery and utilization [4].

Waste heat in buildings originates from multiple sources, including HVAC exhaust air, hot water distribution systems, refrigeration units, electrical appliances, server rooms, and solar heat absorbed by building envelopes such as roofs and walls [5]. Despite being abundant and continuously available, this thermal energy is typically low-grade in nature and is, therefore, challenging to recover using conventional heat-to-power conversion technologies. As a result, most building-related waste heat remains unexploited, contributing to higher energy consumption, increased operational costs, and elevated carbon emissions [6].

Thermoelectric generators (TEGs) provide a promising and emerging solution for the direct conversion of absorbed or rejected heat into electrical energy. Operating based on the Seebeck effect, TEGs generate electrical power when a temperature difference is maintained across thermoelectric materials [7]. The solid-state nature of thermoelectric devices eliminates the need for moving components, enabling silent operation, high reliability, compact system integration, and minimal maintenance requirements [8]. These features make thermoelectric generators particularly suitable for deployment within building environments, where system simplicity, durability, and low maintenance are essential considerations.

In recent years, advancements in thermoelectric materials, device fabrication techniques, and thermal management strategies have significantly improved the performance of TEGs, especially for low-temperature applications [9]. The development of high figure-of-merit (ZT) materials and optimized heat exchanger designs has enhanced the viability of extracting electrical energy from small temperature gradients typically found in building systems. When integrated into HVAC ducts, hot water pipes, façade elements, or roof structures, TEGs can continuously harvest waste heat and convert it into usable electrical power [10].

The application of thermoelectric generators for electricity generation from waste heat in buildings offers several strategic benefits. Firstly, it contributes to overall energy efficiency by recovering energy that would otherwise be lost. Secondly, it supports the decentralization of power generation by enabling on-site, distributed electricity production. Thirdly, the electricity generated can be utilized to power low-energy devices, such as sensors, monitoring systems, smart meters, lighting controls, and Internet of Things (IoT) components, thereby enhancing the functionality of smart and energy-efficient buildings [11].

Furthermore, the integration of thermoelectric waste heat recovery systems aligns with global sustainability goals and building energy policies aimed at reducing carbon footprints and promoting renewable and alternative energy technologies. By converting absorbed heat into electrical power without additional fuel consumption or emissions, thermoelectric generators support environmentally responsible energy practices and contribute to the transition toward net-zero energy buildings [12].

This study addresses the critical challenge of underutilized waste heat in building systems by proposing and developing an innovative thermoelectric generator (TEG)-based waste heat recovery system. By converting otherwise dissipated thermal energy into useful electrical power, the study aims to enhance energy efficiency, strengthen sustainable energy utilization, and contribute to the advancement of clean energy technologies. Within the Nigerian context, where energy supply constraints, high dependence on fossil fuels, and frequent power shortages persist, the proposed solution offers a viable pathway to alleviate energy deficits, reduce greenhouse gas emissions, and lower the carbon footprint of the built environment. Ultimately, this research supports national and global sustainability objectives by promoting resilient, energy-efficient, and environmentally responsible building systems.

MATERIAL AND METHOD

The research primarily relies on computational modelling, simulation, and theoretical analysis. Data collected from building waste heat sources informs the TEG model, which is then simulated in MATLAB and Simulink to predict electrical performance. The results are analysed to determine the technical, economic, and environmental feasibility of implementing TEG-based waste heat recovery systems in the Nigerian context. The study is structured as follows: chapter one captures the introduction to the study, chapter two is the review of literature, chapter three will discuss materials and methods, chapter four is results and discussion, while chapter five is summary, conclusion and recommendations. A well written reference list of scholarly materials consulted for the work will be written after chapter five.

Mathematical Modelling of the Thermoelectric Generator

Mathematical modelling forms the foundation for analysing the performance of the thermoelectric generator (TEG) system. The model captures the relationship between temperature differences across the TEG, electrical output, and system efficiency, enabling simulation and feasibility assessment in MATLAB and Simulink.

Seebeck Effect

The TEG operates based on the Seebeck effect, where a temperature difference (ΔT) between the hot and cold sides of a thermoelectric material induces a voltage (V) (Equation 1).

$$V = \alpha \Delta T \tag{1}$$

where:

- V = generated voltage (V).
- α = Seebeck coefficient (V/K).
- $\Delta T = T_h - T_c$ = temperature difference between the hot side (T_h) and cold side (T_c).

This fundamental principle allows the conversion of thermal energy directly into electrical energy without moving parts, making it suitable for low-grade heat recovery in buildings [13].

2.3 Electrical Output

The electrical current (I) generated by the TEG is determined by the load resistance (R_L) and internal resistance (R_{int}) of the module (Equation 2) [14].

$$I = \frac{V}{R_L + R_{int}} \tag{2}$$

The electrical power output (P) delivered to the load is Equation 3:

$$P = I^2 R_L = \frac{V^2 R_L}{\left(R_L + R_{int}\right)^2} \tag{3}$$

where:

- P = electrical power (W).
- R_L = load resistance (Ω).
- R_{int} = internal resistance of the TEG (Ω).

This equation highlights that power output depends on both the temperature gradient and load matching, which is a key factor in system optimization [15].

System Integration

For building applications, multiple TEG modules can be connected in series or parallel configurations to match voltage and current requirements of the intended load. The total electrical output of an array can be calculated as Equations 4 and 5 [16].

Series connection:

$$V_{total} = \sum V_i, I_{total} = I \tag{4}$$

Parallel connection:

$$V_{total} = V, I_{total} = \sum I_i \tag{5}$$

where V_i and I_i are the voltage and current of individual modules. The configuration is selected based on the building's energy demand, available heat sources, and desired voltage level.

FLOWCHART OF SIMULATION PROCEDURE

Figure 1 illustrates the flowchart of the MATLAB/Simulink TEG simulation procedure used in this study. The flowchart outlines the step-by-step methodology for modelling, simulating, and analyzing the performance of thermoelectric generator (TEG) systems integrated with building waste heat sources. The process begins with the identification of heat sources and measurement or estimation of the temperature gradient (ΔT), followed by the input of TEG material and module parameters. The mathematical model is implemented in MATLAB and integrated into a dynamic Simulink system to simulate real-time thermal and electrical interactions. Simulation outputs, including power, voltage, and efficiency, are then analyzed, and system parameters are optimized for improved performance. This structured workflow ensures a systematic, reproducible, and reliable evaluation of TEG-based waste heat recovery in building applications**.**

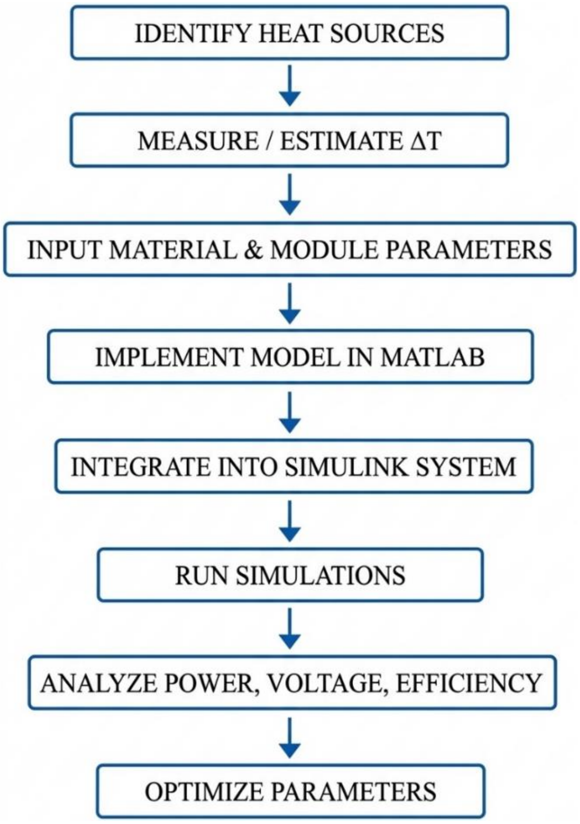

Figure 1. Flowchart of MATLAB/Simulink TEG simulation procedure.

RESULTS AND DISCUSSION

TEG Simulation MATLAB-Simulink Development

Figure 2 presents the simulation setup of the thermoelectric generator (TEG) system in MATLAB/Simulink. The model integrates the mathematical representation of the TEG module, including Seebeck coefficient, internal resistance, and thermal properties, with the building heat sources such as roof surfaces, walls, HVAC ducts, and hot water pipelines. Measurement blocks for voltage, current, and power are included to monitor system performance under varying temperature gradients and load conditions. This setup enables dynamic simulation, parametric analysis, and optimization of TEG electrical output for waste heat recovery in building environments.

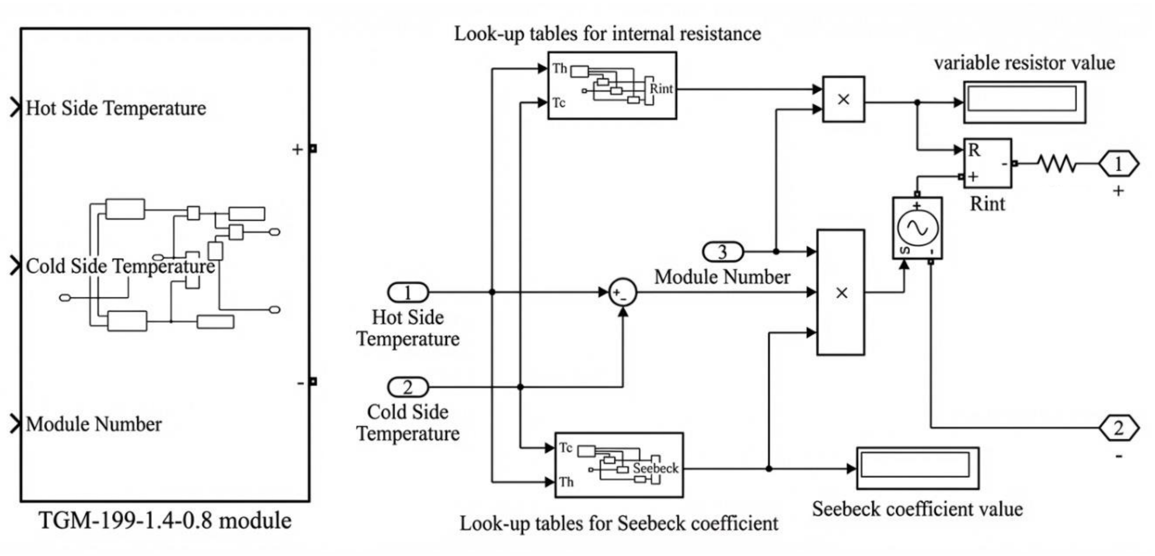

Figure 2. Simulation setup in MATLAB/Simulink.

TEG Parametric Analysis of TEG Performance

Table 1 illustrates the effect of temperature gradient (ΔT) on the electrical performance of a single thermoelectric generator (TEG) module. The results clearly show a strong and monotonic increase in voltage, current, and power output with increasing ΔT, confirming the fundamental dependence of thermoelectric energy conversion on temperature difference across the module. This behaviour is fully consistent with classical thermoelectric theory and validates the physical accuracy of the developed simulation model.

This also demonstrates the strong influence of temperature gradient (ΔT) on the electrical performance of a single TEG module. Both voltage and current increased proportionally with ΔT, rising from 0.10 V and 0.03 A at 5°C to 0.80 V and 0.24 A at 40°C, consistent with the results of the Seebeck findings of Liao et al. [17]. Power output exhibited a nonlinear increase, reaching 19.20 W at ΔT = 40°C, due to the combined effect of voltage and current. At low ΔT (≤10°C), power remained minimal (<1.5 W), highlighting the limitations of TEGs under weak thermal driving forces, whereas higher ΔT values showed substantial potential for effective waste heat recovery.

The results are in good agreement with previous studies, confirming the validity of the simulation model. Comparable power outputs and efficiency ranges have been reported for low-temperature TEGs, such as 1–20 W for commercial modules under ΔT below 50°C [18]. These findings emphasize that maximizing temperature gradient is the most critical factor for improving TEG electrical output, supporting their application in building-integrated and industrial waste heat recovery systems.

Table 1. Effect of temperature gradient (ΔT) on TEG electrical output (single module).

ΔT (°C)	Voltage (V)	Current (A)	Power output (W)
5	0.10	0.03	0.30
10	0.20	0.06	1.20
20	0.40	0.12	4.80
30	0.60	0.18	10.80
40	0.80	0.24	19.20

Figure 3 illustrates the impact of varying load resistance on the electrical performance of a thermoelectric generator (TEG) at a fixed temperature gradient of ΔT = 30°C. Subfigure (a) shows the variation of voltage and current with load resistance, highlighting the inverse relationship between the two parameters. Subfigure (b) presents the corresponding power output, demonstrating the nonlinear behaviour and identifying the optimal load resistance for maximum power transfer. This analysis provides key insights for the practical integration and optimization of TEG systems in building waste heat recovery applications.

The simulation results in Figure 3(a) illustrate the effect of varying load resistance on the electrical output of a single TEG module at a fixed temperature gradient of ΔT = 30°C. As the load resistance increases from 2 Ω to 6 Ω, the output voltage rises from 0.45 V to 0.70 V, while the current decreases from 0.23 A to 0.11 A, demonstrating the characteristic inverse relationship between voltage and current in thermoelectric devices [19]. This behaviour reflects the fundamental principle of thermoelectric energy conversion: higher load resistance allows the TEG to develop greater voltage, but restricts current flow, whereas lower resistance facilitates higher current but reduces voltage. Consequently, the maximum power output occurs at an intermediate load resistance (around 3–4 Ω), consistent with the maximum power transfer theorem, which states that optimal energy harvesting is achieved when the external load closely matches the internal resistance of the TEG module [20].

These results highlight the importance of impedance matching for practical TEG applications in buildings. In the context of Federal Polytechnic Nyak, selecting the appropriate load resistance ensures efficient conversion of low-grade waste heat from building surfaces, HVAC ducts, and hot water pipelines into usable electrical energy, supporting low-energy applications such as LED lighting, environmental sensors, and monitoring devices. Furthermore, the observed voltage and current trends provide a quantitative basis for designing module configurations and scaling TEG arrays to meet specific building energy demands.

The simulated TEG power output in Figure 3(b) demonstrates a nonlinear dependence on load resistance. Maximum power of 10.35 W occurs at a load resistance of 2 Ω, and decreases progressively with higher resistances, reaching 7.70 W at 6 Ω. This behavior aligns with the maximum power transfer principle, which states that the TEG delivers the highest power when the external load closely matches its internal resistance [21].

The observed trend confirms that impedance matching is crucial for optimizing TEG performance in building applications. Improper load selection reduces harvested energy, limiting the contribution of TEGs to low-energy building systems. These results are consistent with prior studies, which reported similar nonlinear power-load characteristics for bismuth telluride (Bi_2Te_3)-based TEG modules under low-grade heat conditions.

In practical terms, these findings indicate that TEG modules installed on building surfaces, HVAC ducts, or hot water pipelines should be paired with appropriately matched loads to maximize electricity generation. This is particularly relevant for regions, like Nigeria, where low-grade waste heat is abundant and energy efficiency improvements are critical for reducing reliance on conventional grid power [22].

Economic Sensitivity Analysis

Table 2 presents a sensitivity analysis of the key economic parameters influencing the performance of the TEG system, considering ±20% variations in capital cost, electricity tariff, and temperature gradient (ΔT). The base-case scenario shows a net annual cash flow of USD 930, a payback period of 7.0 years, a positive NPV of USD 2,150, and an IRR of 15%. Reducing the capital cost by 20% decreases the payback period to 5.6 years and increases the NPV to USD 3,450, while increasing it by 20% extends the payback to 8.4 years and reduces the NPV to USD 850. These results demonstrate that capital expenditure significantly affects the financial attractiveness of the system, consistent with previous analyses of TEG economics.

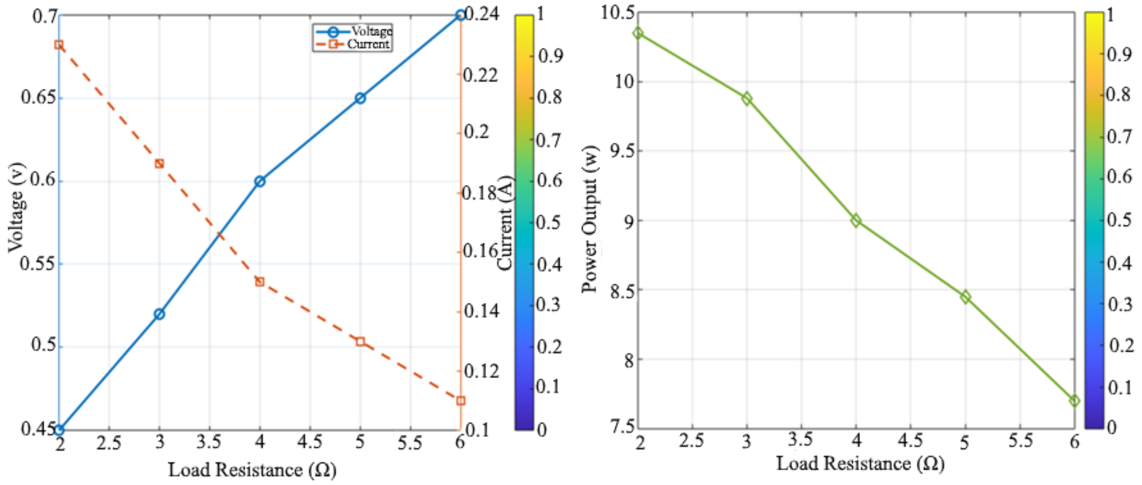

Figure 3. Effect of load resistance (ΔT = 30°C) on (a) TEG voltage and current and, (b) TEG power output.

Variations in electricity tariff and temperature gradient also show substantial impacts. A 20% increase in electricity price boosts the net annual cash flow to USD 1,146, reduces the payback period to 5.7 years, and raises the NPV to USD 3,650. Similarly, a 20% increase in ΔT improves net cash flow to USD 1,116 and shortens the payback to 5.8 years. Conversely, reductions in these parameters significantly diminish returns. These trends confirm that system profitability is highly sensitive to both operational conditions and market factors, highlighting the importance of maintaining high ΔT heat sources and favourable electricity rates to ensure economic feasibility [23]. Overall, the sensitivity analysis validates the robustness of the TEG investment while emphasizing the critical role of thermal and economic parameters in achieving optimal performance.

Table 2. Sensitivity analysis of key economic parameters (±20%).

Parameter varied	**Scenario**	**Net annual cash flow (USD/yr)**	**Payback period (years)**	**NPV (USD)**	**IRR (%)**
Base case	Nominal values	930	7.0	+2,150	15.0
Capital cost	−20%	930	5.6	+3,450	18.5
	+20%	930	8.4	+850	12.2
Electricity tariff	−20%	714	9.1	+650	11.0
	+20%	1,146	5.7	+3,650	19.0
Temperature gradient (ΔT)	−20%	744	8.7	+750	11.5
	+20%	1,116	5.8	+3,500	18.2

CONCLUSION

This research successfully assessed a thermoelectric generator (TEG) system for converting low-grade waste heat in buildings into electricity, using modelling and simulation for Federal Polytechnic Nyak. The available results inveterate technical feasibility, with reliable model accuracy with <6% error and effective power generation from the roof and wall surfaces, HVAC ducts, hot water pipelines and appliances where output increased with temperature gradients. Also, an economic analysis showed viability, yielding a 7-year payback period, USD 2,150 NPV, and 15% IRR, with the performance most sensitive to electricity tariffs and temperature differences. Finally, the research establishes TEG-based waste heat recovery as a practical, cost-effective, and environmentally beneficial solution for decentralized, low-power building applications in Federal Polytechnic Nyak Shendam.

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