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THERMOELECTRIC GENERATORS IN AUTOMOTIVE APPLICATIONS: A COMPREHENSIVE REVIEW OF CONCEPTS, MATERIALS, AND INTEGRATION STRATEGIES

BY

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Abstract. The transportation sector accounts for nearly one quarter of global primary energy consumption, with internal combustion engines losing more than two-thirds of their fuel energy as waste heat. In the context of the growing interest in energy efficiency and reduction of pollutant emissions, thermoelectric devices stand out as a promising solution, capable of transforming residual thermal energy into electrical power through the Seebeck effect. Use of thermoelectric generators in automobiles is attracting increased interest from the industrial and scientific communities, as harnessing energy from waste heat within exhaust gases may significantly improve energy conversion efficiency, reduce fuel consumption, without moving parts, in a silent, compact and reliable manner. Nevertheless, the widespread adoption remains limited due to low conversion efficiency, material costs, and integration challenges in dynamic vehicle environments.

This analysis contributes to a better understanding of the thermoelectric devices potential use in automotive applications and outlines future directions for

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research and development. In addition, the development of more thermally efficient architectures and the combination with energy storage systems could lead to more viable solutions for electric and hybrid vehicles.

Keywords: Thermoelectric generator; Waste energy; Exhaust waste heat; Seebeck effect; Heat Recovery Systems.

1. Introduction

Environmental pollution, climate change, and rising energy costs are the main challenges we are facing nowadays. Moreover, for the global automotive industry energy efficiency and emissions reduction represent critical objectives. Only about one-third of the chemical energy in fuel is converted into mechanical work by conventional internal combustion engines (ICEs); the rest is lost as heat through coolant and exhaust systems (Sivaprahasam, 2018; Hannu, 2023; Ivanov, 2020). With increasingly stringent CO_2 regulations and sustainability goals, recovering even a small portion of wasted heat offers a significant opportunity to improve overall vehicle efficiency and reduce environmental impact.

Thermoelectric generators (TEGs) have attracted growing attention as a compact, solid-state solution for waste heat recovery. Operating on the Seebeck effect, a TEG directly converts a temperature gradient into electrical energy without moving parts or working fluids. Unlike conventional heat engines or Rankine-based recovery systems, TEGs are lightweight, maintenance-free, and capable of dynamic operation under varying thermal conditions–making them well suited for automotive integration. In addition to improving fuel economy, TEGs can supply auxiliary power for sensors, control units, and comfort systems, thus reducing alternator load and improving engine efficiency. Moreover, these devices are ecologically sustainable as they do not operate with chemical substances, and function silently due to the absence of mechanical structures and/or moving components (Nesrine, 2020).

The thermoelectric effect encompasses three interrelated phenomena: Seebeck, Peltier, and Thomson effects. The Seebeck effect, in particular, enables the generation of voltage when two dissimilar semiconductors are exposed to a temperature difference. The efficiency of a thermoelectric device is determined by the material's dimensionless figure of merit, *ZT*, that depends on the Seebeck coefficient, electrical and thermal conductivity, as well as absolute temperature. Achieving high *ZT* values requires materials that simultaneously exhibit high Seebeck coefficients and electrical conductivity while maintaining low thermal conductivity, an inherently challenging balance.

Over the past two decades, extensive research into new thermoelectric materials has led to remarkable performance improvements. Even if traditional Bi_2Te_3-based materials remain dominant for low-temperature applications (i.e.

<250°C), new developed materials and alloys as PbTe, SiGe, skutterudites, and half-Heuslers have demonstrated superior performance at higher temperatures relevant to automotive exhaust systems (Chen and Ren, 2013).

Parallel advances in nanostructuring, doping, and composite engineering continue to push values for the figure of merit toward the 2 - 3 range, bringing thermoelectric conversion closer to practical viability in systems for various vehicles (Achitei *et al.*, 2023).

The present work aims to provide basic information for future studies on material developments and system integration by highlighting the need for high-efficiency thermoelectric materials to meet the growing concerns of energy waste and environmental impact (Zhi-Gang, 2012). This review focuses on three principal areas relevant for automotive applications:

– the operating principles, efficiency limits, and performance modelling of TEG systems;

– progress in thermoelectric materials suitable for automotive temperature ranges, along with mechanical and environmental considerations;

– strategies addressing system-level design, thermal and electrical management, and real-world prototype implementations.

Furthermore, an in-depth study of this area should be concerned with evaluation of techno-economic aspects, environmental impacts, and end-of-life management of thermoelectric modules, reflecting the increasing importance of sustainability and circular-economy principles in automotive engineering. But these topics are not covered in this paper and will be tackled in future research.

2. Thermoelectric Principles

Thermoelectric generation relies on three closely related phenomena, i.e. Seebeck, Peltier, and Thomson effects. Among these, **Seebeck** effect is the basic thermoelectric (TE) phenomena, identified in 1821, represents the basic idea for power generation in TEGs. The Seebeck effect was initially identified in 1774 by the Italian scientist Alessandro Volta, but it was independently discovered and given the name in 1821 by the physicist Thomas Johann Seebeck (Seebeck and Octtingen, 1895; Goupil, 2011). It states that an electric voltage occurs when a temperature gradient is present across different conductors or semiconductors, (Ando Junior *et al.*, 2018). The material's characteristics and temperature difference across determine the induced voltage (Xingyi *et al.*, 2019; Achitei *et al.*, 2023):

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

where α is the Seebeck coefficient [$V \cdot K^{-1}$] = magnitude of the thermoelectric voltage produced per unit temperature difference. Typical Seebeck coefficients for efficient thermoelectric materials range from 100 to 300 [$\mu V \cdot K^{-1}$].

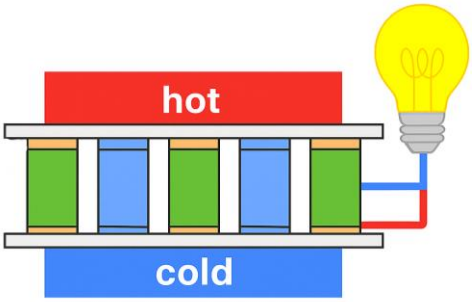

Fig. 1 − Schematic visualization of the Seebeck effect.

According to the Seebeck effect, as illustrated in Fig. 1, the temperature difference in thermoelectric materials (semiconductors, conductors) will cause a shift in electrical carriers within. As a result, an electrical potential occurs, thus accomplishing a transition from thermal to electric energy.

The **Peltier** effect, discovered by Jean Charles Athanase Peltier in 1834, is the opposite of the Seebeck effect. It refers to the absorption or emission of heat when an electric current travels over a junction of two distinct conductors or semiconductors.

William Thomson (Lord Kelvin) discovered the **Thomson** effect in 1851, that relates to heat absorption or emission within a single homogeneous conductor under a temperature gradient and current flow.

From thermodynamic point of view, these effects are interrelated and can be derived from Onsager reciprocal relations ensuring energy conservation within the thermoelectric couple (Ågren, 2022).

Thermoelectricity is the direct conversion of heat into electricity or vice versa. Joule's law states that an electrical current flowing through a conductor creates heat according to its resistance (R) and current (I). A thermocouple is a single circuit of this sort, while a thermopile is a sequence of thermocouples (Govind and Sharma, 2017). A typical TEG module is made up of 10 to 100 thermoelectric elements of type ***n*** and type ***p***, electrically coupled in series and thermally in parallel, and sandwiched between two ceramic layers.

The conversion efficiency (η) of a thermoelectric generator, assuming steady-state conditions and small temperature gradients, is determined by

$$\eta = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}}+\dfrac{T_c}{T_h}} \tag{2}$$

Here, T_h and T_c are the hot- and cold-side temperatures, respectively, and ZT is the average figure of merit of the material over the operating temperature range. This equation highlights that higher ZT values directly enhance the conversion efficiency, although the theoretical upper limit remains constrained by the Carnot efficiency, $\eta_{Carnot} = \Delta T/T_h$.

3. Thermoelectric Materials

The dimensionless figure of merit (*ZT*) is a key indicator of a material's thermoelectric performance, characterizing the conversion efficiency depending on transport properties of the material (Zoui *et al*., 2020) and is defined as:

$$ZT = \frac{\alpha^2 \cdot \sigma \cdot T}{\kappa} \tag{3}$$

where:

α = Seebeck coefficient (μV/K) indicates the magnitude of voltage induced per unit temperature gradient

σ = electrical conductivity (1/Ωm) measures material's ability to conduct electric current

T = absolute temperature (K)

κ = thermal conductivity (W/mK) represents the material's heat conduction capacity.

In equation (3) the numerator, $\alpha^2\sigma$, is referred to as the *power factor* (PF) and quantifies a material's ability to convert heat into electrical power.

To maximize *ZT* high Seebeck coefficient and electrical conductivity are required, while thermal conductivity is minimized. This represents a challenging task due to the interdependent nature of these properties. Modern synthesis and characterization techniques are paving the way for complex thermoelectric materials (Snyder and Toberer, 2008).

Recent advancements in thermoelectric science emphasize not only the identification of materials with elevated *ZT* values, but also the optimization of devices and systems through approaches such as thermal interface engineering, reduction of contact resistance, and innovative module shapes (Weishu *et al*., 2012; Yulong *et al*., 2021; Çelik *et al*., 2023).

In practical automotive systems, *ZT* must be evaluated not only at peak temperature, but across the entire operating range of the heat source, since *ZT*(*T*) often varies with temperature. Hence, the average figure of merit, is often used to approximate performance under variable exhaust conditions.

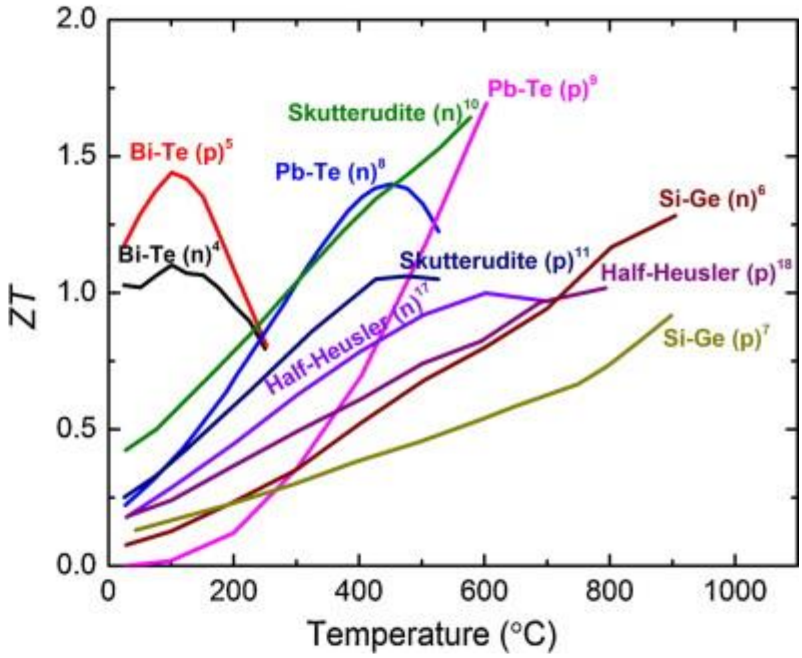

Fig. 2 − *ZT* vs. temperature for different thermoelectric materials (Chen and Ren, 2013).

Thermoelectric materials have an important role in characterising the efficiency and sustainability of TEG systems in automotive applications. These materials must have high electrical conductivity, low thermal conductivity, and a significant Seebeck coefficient (Singh *et al.*, 2024). Most common TE materials used in various applications, including automotive, are described in Table 1.

Table 1
Thermoelectric Materials

Material	ZT	Operating Temp	Comments
Bi_2Te_3	~1.0	25–250	Commercial, stable
PbTe	~1.5	300–500	Toxic, high efficiency
Mg_3Sb_2	>1.5	200–400	Environmentally friendly
SnSe	>2.0	300–700	Excellent ZT, brittle
Half-Heuslers	1–1.5	400–800	Mechanically robust

Bi_2Te_3 and its alloys with Bi_2Se_3 and Sb_2Te_3, PbTe and its alloys with PbSe and SnTe, and SiGe alloys form the basis of classical thermoelectric materials (Zhiting, 2014).

Bismuth telluride is used in TEGs for moderate heat source temperatures. The dimensionless figure of merit (ZT) increases with temperature but decreases above a certain temperature due to minority carrier conduction. Goldsmid (2014) published theoretical predictions in comparison with observed properties and suggested compositional changes are for generator module materials.

Because of its appropriate physical and chemical characteristics, lead telluride is an excellent thermoelectric material. Its high-power factor and notably reduced heat conductivity make it unique. It has a high Seebeck coefficient, low thermal conductivity, good electrical conductivity, and a relatively adequate carrier concentration, among other advantageous characteristics (Sharma *et al*., 2021). The downside of using such material is the toxicity of lead.

The most researched semiconducting materials for TE applications are silicon-germanium, or SiGe. The interest in such semiconductors was sparked by mid-20th century investigations for power systems in space applications, such as satellites optional components. Environment characteristics and maintenance unavailability made SiGe-based TEGs indispensable for this type of applications (Mirando, 2018).

For automotive applications, suitable thermoelectic materials must operate efficiently across a wide temperature range (typically 200–700°C), exhibit high mechanical and chemical stability, and maintain consistent performance under thermal cycling and vibration. In addition to high *ZT*, materials must meet some practical requirements such as thermal and oxidation stability in exhaust or coolant environments, compatibility with metallic contacts and solders, mechanical robustness to withstand vibrations and stress, economic feasibility for large-scale manufacturing.

Because no single material can cover the full exhaust temperature range efficiently, segmented or cascaded TEG modules are often employed, combining low-temperature and high-temperature materials to maximize total efficiency.

4. Automotive Integration Strategies

Electrical integration, thermomechanical design, and energy harvesting efficiency must all be carefully considered for TEGs to be implemented successfully in automobile systems.

Exhaust Heat Recovery. Harvesting thermal energy form waste heat evacuated in industrial and automotive exhaust systems has been the subject of numerous research. In 1963, A.D. Neild created the first exhaust TEG. Over the following 30 years, a number of TEG prototypes for passenger cars have been developed. Large, international corporations (BMW, Renault, Honda, and Ford) carried out research and continued to contribute to the development of automotive exhaust heat recovery systems that use TEGs technology (Asaduzzaman *et al*., 2023; Mori, 2011; Espinosa, 2010; Hussain *et al*., 2009).

Cooling System Integration. An optimal system that includes a thermoelectric generator requires an efficient cooling mechanism to maintain recommended temperature difference across the thermoelectric module. Cooling strategies use electrical or mechanical components to drive heat out of the cool side of the TEG. These techniques consist of either forced air cooling using engine-driven airflow or electric fans, or tubes for liquid cooling that are connected to the car's radiator or a separate component (Wang *et al*., 2025; Brito *et al*., 2019).

Hybrid systems combine multiple heat sources or materials to maximize overall efficiency. One strategy is *Hybrid Heat-Source Integration*, where a dual-stage TEG utilizes exhaust heat for the primary stage and coolant for the secondary stage. The exhaust stage operates at 500-700°C, while coolant stage maintains 100-150°C. This configuration allows recovery of both high- and low-grade heat, yielding higher total system efficiency (5-7%) with lower module stress. The alternative strategy is Material Cascade Configuration, where different TE materials are stacked vertically within the same TEG module (in ***n***- and ***p***-type legs), with high-temperature materials (e.g., skutterudite or half-Heusler) on the hot side and low-temperature Bi_2Te_3 on the cold side. The resulting temperature segmentation ensures each material operates within its optimal range, increasing net output power. Experimental prototypes using skutterudite/ Bi_2Te_3 cascades have reported efficiency gains of 30-40% compared to single-material modules.

Besides the classic strategies mentioned above, some emerging trends in automotive integration include modular plug-and-play TEG designs, 3D-printed heat exchangers, and AI-assisted control strategies that dynamically adjust load and thermal interfaces for optimal energy recovery. Continued innovation in system-level integration and intelligent control will be critical to transitioning thermoelectric generators from prototype to mainstream automotive technology. Therefore, efficient thermal management becomes vital for maximizing ΔT while preventing module degradation. Strategies include advanced heat exchangers with phase-change materials (PCM) or liquid-metal coolants, thermal interface materials (TIMs) with high conductivity and flexibility, active cooling loops with coolant pumps or thermosiphon assisted designs, and compact modular layouts to reduce volume and weight. Also, diagnostic algorithms detect performance degradation due to fouling, oxidation, or thermal fatigue. Predictive maintenance strategies, supported by embedded sensors, are increasingly being incorporated into next-generation automotive TEGs for smart energy recovery management.

5. Advantages and Limits of TEGs

The advantages of TEGs are:

- direct energy conversion, in opposition to typical heat engines, which transform thermal energy into mechanical energy before converting it further into electrical energy
- there are no moving parts or working fluids inside the TEG, so there is no need for maintenance or additional expenses
- no scale effect: TEG can be used for macro- or micro-generation in extremely constrained areas
- any working placement and position is possible (Champier, 2017).

Despite these advantages, there are some limitations in their use, such as:

- low conversion efficiency
- high cost
- toxicity of some materials (Ojha *et al*., 2024; Pei *et al*., 2012).

Despite the considerable progress achieved, thermoelectric generators in automotive applications still face multidisciplinary challenges spanning across materials science, heat transfer, electrical engineering, and sustainability.

Continued advances in material design, manufacturing scalability and system integration are essential to achieve commercially viable, environmentally sustainable solutions. The convergence of new concepts in advanced simulation, artificial intelligence, and circular economy principles will enable the next generation of automotive TEG systems to evolve from experimental prototypes to mass-deployable energy recovery technologies that meaningfully contribute to global decarbonization efforts (Yang *et al*., 2018).

6. Conclusions

Thermoelectric generators (TEGs) provide a strong chance to improve the energy efficiency of automobile systems by transforming waste heat into electrical energy. This review has focused on the thermoelectric principles including the Seebeck, Peltier, and Thomson effects along with recent advances in thermoelectric materials, which offer high efficiency and improved environmental profiles. The performance of this system depends on cooling system design and thermal interface engineering.

Future studies should concentrate on integration into electric and hybrid vehicle platforms, long-term durability, and economical mass production. For thermoelectric energy harvesting to reach its full commercial potential, cooperation between mechanical engineers, materials scientists, and automakers will be essential.

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GENERATOARE TERMOELECTRICE ÎN APLICAȚII AUTOMOTIVE: O REVIZUIRE CUPRINZĂTOARE A CONCEPTELOR, MATERIALELOR ȘI STRATEGIILOR DE INTEGRARE

(Rezumat)

Generatoarele termoelectrice (TEG) reprezintă o tehnologie inovatoare cu un potențial ridicat pentru valorificarea căldurii reziduale. În contextul interesului crescut pentru eficiența energetică și reducerea emisiilor de poluanți, generatoarele termoelectrice (TEG) se remarcă ca o soluție promițătoare, capabilă să transforme energia termică reziduală - în special cea din gazele de eșapament ale motoarelor cu ardere internă - în energie electrică, ceea ce poate reduce semnificativ consumul de combustibil, fără piese în mișcare, într-un mod silențios și fiabil. Utilizarea TEG-urilor în automobile atrage un interes crescut din partea comunităților industriale și științifice. Această analiză contribuie la o mai bună înțelegere a potențialului TEG-urilor în aplicațiile auto și conturează direcțiile viitoare pentru cercetare și dezvoltare. În plus, dezvoltarea unor arhitecturi mai eficiente din punct de vedere termic și combinarea TEG-urilor cu sisteme de stocare a energiei ar putea duce la soluții mai viabile pentru vehiculele electrice și hibride.