Economic and Environmental Benefits of Thermoelectric Generators

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Abstract
All modern systems rely on energy to function, yet two-thirds of the global energy consumption is lost as heat. This project explores a suitable method of salvaging the lost thermal energy, providing economic incentives and environmental benefits. Thermoelectric generators (TEGs) are capable of harvesting this thermal energy. This will put less stress on nonrenewable fuel sources such as fossil fuels and reduce the pollution they cause. Using automobiles and microelectronics as test subjects in this paper, TEGs have proven to be viable solutions for capturing and repurposing waste heat.

I. Introduction/Motivation

Energy is essential to all modern processes, from transportation to everyday electronics. Approximately 63% of global energy consumption is lost as heat during combustion and heat transfer processes such as operating engines and running microelectronics[1]. This energy loss is often called “waste heat” and is dissipated into the environment. Not only is the energy loss inefficient and results in more energy consumption but the expense is also added to the engines or electronics to properly vent the excess heat away from the functioning system. Economically and environmentally, it is beneficial to minimize the amount of heat lost and instead reuse this energy as input energy for the intended application.

As more fossil fuels are burned to compensate for this inefficiency, more pollution and greenhouse gases are released into the air. This has enhanced the natural greenhouse effect, resulting in the dangerous consequences of climate change, including extreme weather patterns, extinction of animals, loss of natural habitat, and rising sea levels. Furthermore, this process results in significant economic losses as most input energy is wasted, leading to higher production costs. And finally, companies bear extra costs by adding materials and systems to exhaust this waste heat. In response to these issues, it is imperative to find a way to recover and repurpose this thermal energy.

Notable theories and work to convert heat into electrical energy started as far back as the 1820s when Thomas Johan Seeback found that a temperature difference between two conductors caused a movement of charge carriers[2]. This created the first thermoelectric generator (TEG). While seemingly promising, these early investigations had very low efficiency and required large additions of material and circuitry to implement effectively. Cheaper energy sources and a lack of concern for pollution prevented large-scale deployments of this technology. With advances in understanding the process and improved materials and construction of TEGs, generating electrical energy via this concept has become more efficient, and the costs to implement them have decreased. In addition, the drive to lower operating costs, including the cost of energy used, and lowering the effects of pollution from large-scale energy plants and gasoline combustion engines has renewed interest in evaluating the effectiveness of this technology today.

Waste heat can be found in various sectors. The following sections will provide a brief discussion of TEG theory and explain how TEGs can benefit automobiles and microelectronics.

II. TEG Theory

Thermoelectric generators are a potential solution for harvesting energy from waste heat. These devices can be implemented with solid-state semiconductors that utilize the Seebeck effect to create energy from a temperature difference. The Seebeck effect occurs due to the movement of charge carriers, either electrons or holes, between two different conductors. This build-up creates an electric potential difference that is directly proportional to the temperature difference across the semiconductor, as illustrated in Figure 1.

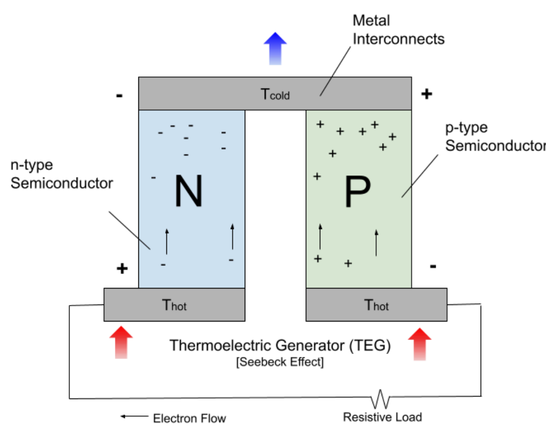

Figure 1: Model of TEG. N-type semiconductor has excess electrons (-), while the P-type has excess holes (+). The electrons and holes move to create an electric potential difference that is proportional to the temperature difference across the device. Figure replicated from Applied Thermoelectric Solutions[3].

More explicitly, to build a TEG, there will be a substrate where heat is absorbed (the hotter side) connected to a substrate that is cooler via a metal interconnect. The metal interconnect will have an n-type semiconductor material with an excess of electrons connected to a p-type semiconductor material with more "holes." These "holes" are formed when electrons exit their valence band, leaving a net positive charge in the crystal lattice. By allowing electrons to move from hole to hole, an electric current is generated in the semiconductor material[4]. Silicon is the semiconductor material used in most TEGs, and it can be made p-type or n-type by doping with elements such as boron to its crystalline structure.

The voltage-temperature relationship is defined by the Seebeck Coefficient (S), in units of Volts/Kelvin:

$$V = S * \Delta T$$

where V is the output voltage from the generator in volts, and ΔT is the temperature difference across the TEG in Kelvins where $\Delta T = T_{hot} - T_{cold}$[5].

However, the output voltage (V) drops due to internal generator resistance. Beginning with Ohm's law, $V = I * R$, the equation is adapted to include the generator resistance (R_g). Thus, the current (I) through the load (R_L) becomes[5]:

$$I = \frac{S * \Delta T}{R_g + R_L}$$

The generator output (I), the output voltage (V), and the heat input in watts (Q) can be manipulated to find the efficiency of the generator (η)[5]:

$$\eta = \frac{V * I}{Q}$$

According to these principles, the larger the temperature difference, the greater the amount of energy that will be created. Regarding efficiency, TEGs are bound by Carnot's Theorem, which creates an upper limit on the efficiency of a heat transfer based on the second law of thermodynamics.

$$\eta_{max} = 1 - \left(\frac{T_{cold}}{T_{hot}}\right)$$

However, the specific method and equipment, along with outside factors, dictate how far below the ideal efficiency the device will operate. This is often more than 20% below the calculated efficiency[6].

Modern technological innovations have allowed for various developments regarding thermoelectric technology that address concerns about cost and efficiency. Firstly, TEGs function without any moving parts. This reduces the need for maintenance and, therefore, lowers the cost of replacements as the lifespan of the technology is relatively long. Second, TEGs can now be constructed in a small form factor, which allows them to be used in a wider range of applications. This includes small devices such as electronics. Furthermore, when connected in series, TEGs can achieve a higher output power while maintaining a small height.

IV. TEG Applications

TEG usage can be explored in various locations, including automobiles and small-scale electronics. The following subsections introduce the different kinds of applications.

IV.I Automobiles

Automobiles are responsible for 16.4% of greenhouse gas emissions[7]. Despite significant development in the electric vehicle sector, there has been no drastic change in carbon dioxide emission levels due to the industry's size. Furthermore, the financial barriers to committing to electric vehicles have made it difficult to implement them worldwide, especially in low and middle-income countries. This issue applies to personal vehicles and attempts to improve public transportation. Therefore, small adjustments to improve engine efficiency can reduce fuel consumption and emissions, which is a logical next step. Several technologies show promising results, with the conversion of heat energy produced in the engine to electricity via a thermoelectric generator gaining much attention. This technology is particularly interesting due to its simplicity and long lifespan.

Currently, two-thirds of the total heat produced by fuel combustion goes to waste. A TEG would convert this waste heat into electricity that can be stored and utilized for various electrical inputs of a vehicle. This idea is demonstrated in Figure 2. As the efficiency of TEGs is quite low, the question of the true benefits of this solution is raised. To increase efficiency, the temperature difference between the hot and cool sides of the generator must be increased. Cars can accomplish this by connecting one end of the device to the engine coolant circuit. This cooling system, otherwise known as the radiator, was tested to find the maximum temperature difference, which was found to be 80˚C. Using a Bi_2Te_3-based TEG with low engine loads, over 1kW of electrical power was generated[8]. This is enough to self-supply the alternator and significantly reduce fuel consumption.

The exhaust heat system is the other location that could achieve a serious temperature difference. The hot gas expelled from the engine can be contrasted with the coolant heat

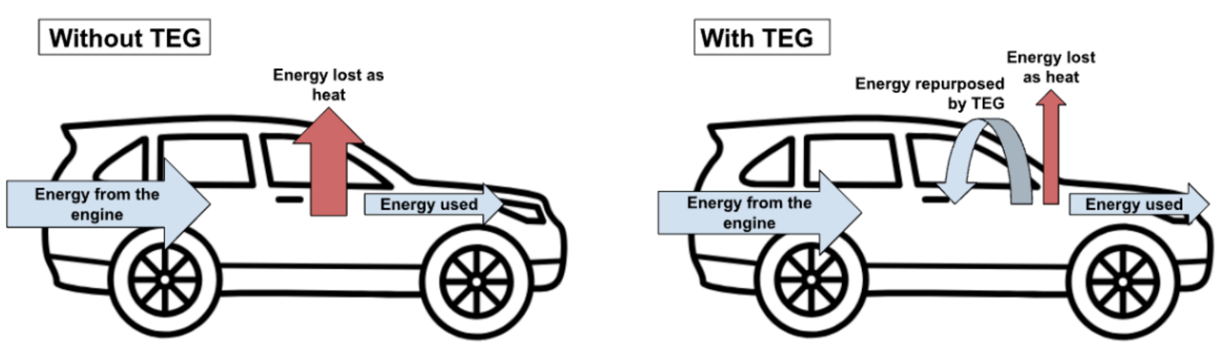

Figure 2: Model of the effects of adding a TEG on the amount of relative energy lost as as heat and therefore the amount of energy needed to power the vehicle.

exchanger, which uses liquid coolant to maintain a cold temperature. This system has proven a temperature difference of 200°C, which generated 14 W of power when using 32 TEG modules[8]. However, the complexities of designing a system that includes many TEG modules lower the cost efficiency. Furthermore, key challenges, such as maintaining a homogenous temperature difference across the surface, decrease the efficiency. This creates further limitations to the idea, requiring additional insulation systems for TEGs to absorb the heat more directly from the heat exchanger. With technological developments to address the current issues, this method would be another viable location for implementing thermoelectric generators in automobiles.

The fuel cost savings of the vehicle owner depend on the price of fuel used to power the car and the efficiency of the thermal energy conversion process. When using a fuel price of $3.01/gallon with a 10% power efficiency of the TEG module, the fuel cost savings would be around $0.60/gallon. This makes the energy/fuel cost-saving efficiency 20% per gallon[8].

Overall, automobiles produce significant amounts of greenhouse gas emissions, and two-thirds of the fuel they use is not even used to power the engine but rather dissipated as waste heat. Adding TEGs to cars would provide a way to salvage this heat and turn it back into electrical energy. The energy collected can then be repurposed and used to power the car. This process will save the car owners money spent on fuel and lower emissions, creating a net positive economically for the consumer and environmentally as the emissions from combustion of fossil fuels used to power the car will be lowered.

IV.I. Microelectronics

Microprocessors often refer to the elements of computers, such as the central processing units (CPUs) and microchips found in cell phones. Thermoelectric generators in electronics were explored by Edward Suski in 1995 as a response to the need to reduce heat generated by microprocessors[8]. He discovered that adding battery-powered fans to the system was not ideal because they further increased the device's energy consumption and added cost to the system just for the sake of expelling waste heat. Suski invented a method and apparatus for recovering power from semiconductor circuits using thermoelectric generators. The thermoelectric generator's preferred location was between the semiconductor device and a heat sink. The large temperature difference in this location optimized the efficiency and electrical output of the device. To address the initial concerns of cooling the device, this energy was transferred to the power source of the fan[9].

Over time, improvements were made to Suski's invention by using a "shunt attach" configuration. This attachment created an alternative heat track to a shunt heat sink, which enabled electricity to be generated by the TEG module and supplied the power to the cooling fan. The specific setup with this attachment amplified the voltage and generated sufficient electricity to power the cooling fan. This improved the device's efficiency and increased the total power generated to around 10-100 mW. This idea is seen below in Figure 3.

Another example within electronics is the broadband router. This router brings internet to homes and distributes internet data through the house via Wi-Fi or ethernet. A typical broadband internet router costs $70 to $150 to a Telecom operator, who then sells the equipment to homeowners. The device has more than $4 worth of cooling materials and circuitry to remove unwanted heat. These include metal heat sinks, thermal heat transfer pads, thicker ground planes in the PCB board to dump heat into, vents in the plastic casing, and possibly a fan for airflow. Replacing the heatsinks with TEGs will use the temperature difference between the surface of the main microelectronic chips (~125°C) and the room temperature (~20°C). Recovering only 5% of the energy lost due to heat and adding it back into the router lowers its power consumption and the operating cost of the device over its lifetime[10].

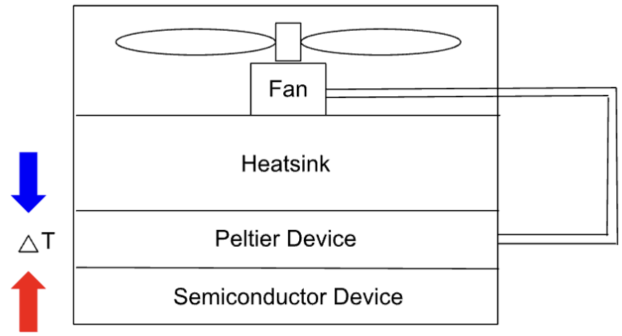

Figure 3: The set up for TEGs in electronics and the relative location that allows for the connection between the cooling fan and the device to operate successfully and create the largest temperature difference. Replicated from Suski's patent for theoretical thermoelectric devices[9].

Considering that electronic devices produce thermal power in the range of 6-320 W with temperatures around 110°C, a large percentage of power is lost as heat in microelectronics[8]. TEGs can be utilized to reduce power consumption by repurposing energy that would be otherwise lost as heat. This solution is beneficial to the environment, as less power will have to be created to power the devices. Furthermore, there are valuable cost savings for the consumer.

V. Conclusion

TEGs are a viable solution that reduces energy loss from heat. They are reliable as they have no moving parts and do not break or wear out. This long lifetime without maintenance lowers costs. Furthermore, TEGs would replace today's various expensive cooling techniques, including fans, heat sinks, and ventilation systems. Other benefits include the characteristics of the technology, such as the compact size, quiet operation sounds, and variety of scales that allow for many uses. TEG circuits are technically and economically promising for several industries. Lastly, they benefit the environment as they are a renewable energy source that can increase energy efficiency.

Regulation can help motivate the case industries, automotive and electronics, with the adoption. In the electronics industry, both voluntary agreements and regulations are driving down the power consumption allowances for electronic devices. The Small Network Equipments energy efficiency agreements for Telecom networking devices are pushing to optimize energy consumption [11]. In Europe, the maximum electricity consumption for broadband devices has been set by the European Code of Conduct power consumption regulations[12]. This drives innovation regarding energy efficiency technology as companies are motivated by competition to create the most desirable products. These regulations will help stimulate further innovation to improve the efficiency of technologies such as TEG's. As the widespread use of TEGs increases, the costs will be driven down. Small improvements in efficiency over wide-scale adoption can greatly impact the energy recovered.

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