REVIEW

Thermoelectric generators and their applications: Progress, challenges, and future prospects

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Our community currently deals with issues such as rising electricity costs, pollution, and global warming. Scientists work to improve energy harvesting-based power generators in order to reduce their impacts. The Seebeck effect has been used to illustrate the capacity of thermoelectric generators (TEGs) to directly convert thermal energy to electrical energy. They are also ecologically beneficial since they do not include chemical products, function quietly because they lack mechanical structures and/or moving components, and may be built using different fabrication technologies such as three-dimentional (3D) printing, silicon technology, and screen printing, etc. TEGs are also position-independent and have a long operational lifetime. TEGs can be integrated into bulk and flexible devices. This review gives further investigation of TEGs, beginning with a full discussion of their operating principle, kinds, materials utilized, figure of merit, and improvement approaches, which include various thermoelectric material arrangements and utilised technologies. This paper also discusses the use of TEGs in a variety of disciplines such as automobile and biomedical.

Keywords: thermoelectric generator (TEG), thermoelectric devices, figure of merit, flexible TEG, automotive exhaust TEG

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1. Introduction

This review deals with the current issues in the field of energy. As known, fossil fuel resources are decreasing and the consequences of global warming force the global community to limit energy needs. This leads to looking for solutions to save energy resources. It is shown that 66% of the primary energy consumed is wasted as heat by classical sources.[1] A fraction of this energy which lost as heat can be recovered using different techniques such as classic thermal machines such as Stirling or Rankine cycle.[2] These cycles are characterized by a high efficiency but they are complex and expensive, and they require the use of moving parts and fluids that causes wear. Several solutions are proposed to achieve this objective, and includes two types: direct and indirect conversions to recover heat as represented in the Fig. 1 which are detailed in the review Ref. [3].

Among these several methods, one approach is to recover this heat using solid-state devices such as thermoelectric materials, which have the benefit of not overlapping with fluids or moving components, resulting in lower greenhouse gas emissions and direct conversion of heat into electricity. As a result, they are quite effective. Nonetheless, they have the drawback of still having a poor conversion efficiency, which has historically confined their development to specialized applications.

Thermoelectric materials are used to develop thermoelectric generator which is made up of a series of thermoelectric modules that are sandwiched between two heat exchangers. Each thermoelectric module consists of a few tens to hundreds of pairs of semiconductor materials that allow a portion of the heat that passes through them to be directly converted into electrical energy. For many years, thermoelectric generators were restricted to space applications: their high dependability justified their usage in powering the great majority of space missions (Voyager, Apollo, Pioneer, Curiosity,...).[4–6] Their high cost and low efficiency, however, have restricted their development for more common applications. In recent years, the introduction of new thermoelectric modules with extended operating ranges, low-cost, non-toxic materials, and a small environmental footprint opens up enormous opportunities for manufacturers.[7–10] The development of thermoelectric generators is hindered by three major obstacles: thermoelectric materials, the construction of thermoelectric modules, and the integration of the modules into systems in order to build efficient thermoelectric generators.[11] Many studies now research novel massive or nanostructured materials in order to increase performance and minimize costs.

The aim of this review is to provide the necessary information and to contemplate the usage of thermoelectric generators. Herein, we will offer a detailed TEG state-of-the-art. We will also look at the most recent thermoelectric materials and keys for generating high-efficiency power factors. In addition, we will discuss different types of TEGs architecture and mod-

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ule design. In addition, we will discuss the usage of TEGs in high and low-power biomedical applications.

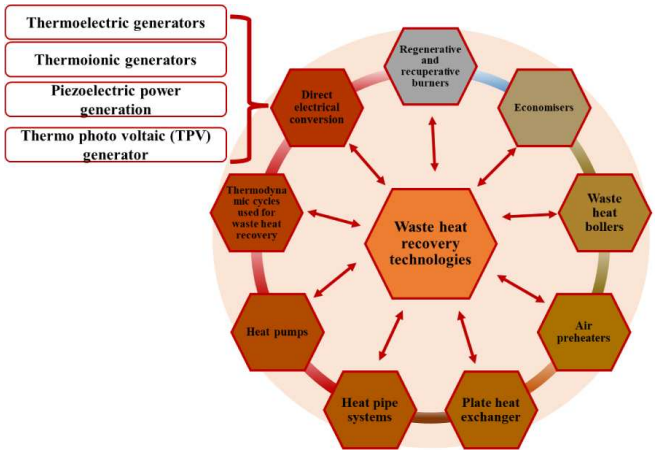


Fig. 1. Representation of various technologies for waste heat recovery.

2. Basics of thermoelectricity

2.1. Seebeck coefficient

A material's thermoelectric behaviour may be identified when the difference in temperature produces a potential difference. This phenomenon was discovered by Thomas Seebeck in 1821, he defined a Seebeck coefficient for a material expressed in $\mathrm{V{\cdot}K^{-1}}$ which represents the voltage generated when the material is exposed to a temperature gradient of 1 K. It can be defined by the following formula:

$$\alpha = -\frac{\Delta V}{\Delta T}, \tag{1}$$

where ΔV represents potential difference and ΔT is temperature difference.

2.2. Peltier effect

In the case of the Peltier effect, an electric current I is applied to the circuit, causing a heat release Q at one junction and a heat absorption at the other. The Peltier coefficient AB is then defined as follows:

$$\Pi_{AB} = \frac{Q}{I}. \tag{2}$$

If a current is applied in the direction of AB, it causes heat release in B and absorption in A, then Π_{AB} is positive.

2.3. Figure of merit ZT

The study of thermoelectric materials was intensified in the 1950s, in particular by the physicist Ioffe.[12] He proved that the conversion efficiency of a thermoelectric material is an increasing function of the dimensionless coefficient called figure of merit which is defined by the following expression:

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

where σ represents electrical conductivity, κ being the thermal conductivity, α being the Seebeck coefficient, and T being the absolute temperature.

When a TE material is exposed to a temperature difference, the charge carriers are moved and create a potential difference. When equilibrium is reached, this difference in potential is exactly opposite of the effect of the temperature difference. The created voltage is proportional to the temperature difference. The proportionality coefficient is called the Seebeck coefficient and noted α. A positive Seebeck coefficient means that the majority charge carriers are holes (P-type), and a negative α means that the majority charge carriers are electrons (N-type).

The efficiency of these materials is related to the dimensionless figure of merit (ZT) which is proportional to the electrical conductivity, the square of the Seebeck coefficient, the average temperature of the material and it is inversely proportional to the thermal conductivity. When the ZT is equal to or greater than one, the material is likely to be employed in an industrial application. A major part of the current research is aimed at increasing the value of ZT by optimising the value of these transport parameters. Thus, to obtain an interesting value of ZT, it is necessary to try to increase the Seebeck coefficient as much as possible to obtain the highest possible voltage, to increase the electrical conductivity in order to minimise the internal losses by Joule effect and to decrease the thermal conductivity as much as possible in order to maintain a significant temperature gradient. The difficulty here is that all these transport parameters are interdependent. In other words, increasing one of these parameters often means degrading the others.[13] For example, a higher electrical conductivity necessarily results in an increase in the amount of heat transported by the charge carriers. This leads to a lower increase in thermal conductivity. This is why progress in the field of thermoelectricity has been relatively modest until recently, when a compromise between these different parameters was made. Recent works have shown that at least some of these limitations is possible to overcome.[14,15]

2.4. Evolution of thermoelectricity field over the years

Figure 2 depicts the evolution of the number of international publications and citations in the field of thermoelectricity. This subject of study was revived in the 1990s after a theoretical study showed that the conversion efficiency of these materials could be improved by nanostructuring. Since then, the number of studies carried out on this subject has grown exponentially each year. The aim of these studies is generally to adjust the composition and structure of a material to maximise its efficiency.

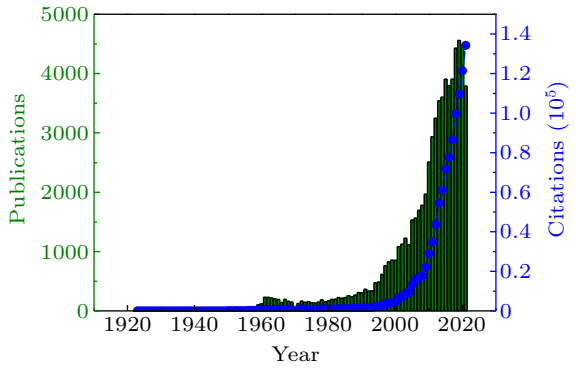


Fig. 2. Data obtained from the ISI web of knowledge database with thermoelectric search option.

3. Basics of TEG

Thermoelectric materials are commonly used in thermoelectric generator for harvesting energy. These devices operate with the help of so-called thermoelectric materials. When one of these materials is exposed to a temperature difference, it generates an electrical voltage. Its connection to an external circuit generates an electric current that can be used to power applications. Thermoelectric generators are self-contained systems comprised of nearly unbreakable semiconductor components that convert a temperature difference and heat flow into a viable direct current (DC) power source (Fig. 3). A TEG consists of n pairs of P-type and N-type semiconductor elements that are electrically connected in series, in order to generate higher voltage and electrical power, and thermally connected in parallel to keep each junction formed by the P–N semiconductor elements at the same thermal gradient. A single N-type or P-type component is referred to as a leg or plug. These semiconductor elements are generally sandwiched between two ceramic plates where heat is transferred from the hot side to the cold side.[16–18] The basic structure of a TEG formed by the association of 2 pairs of semiconductor elements P–N semiconductor elements with a resistive electric charge connected to its terminals is presented in the Fig. 3. A heat flow movement via the TEG occurs when the temperature on the hot side is higher than the temperature on the cold side (presence of a temperature gradient), as seen in Fig. 3. The movement of this heat flow through the P–N semiconductor components causes charge carriers (electrons and holes) to be shifted in opposite directions, resulting in the generation of an electric power output with current I and tension V_{out} coupled to the TEG's borners.

The thermocouple is constructed of two distinct materials with opposing Seebeck coefficients as described above that are connected at their ends. The presence of a temperature gradient, $\Delta T = T_{\text{hot side}} - T_{\text{cold side}}$, between the two thermocouples ends produces an electric voltage defined by[19]

$$V_{\text{out}} = n \cdot \alpha_{\text{NP}} \cdot \Delta T, \tag{4}$$

where n is the number of linked thermocouples, ΔT is the temperature gradient between the cold and the hot sides, and $\alpha_{\text{NP}} = \alpha_{\text{N}} - \alpha_{\text{P}}$ is the sum of the Seebeck coefficients of the two connected materials legs N and P that comprise the thermocouple.

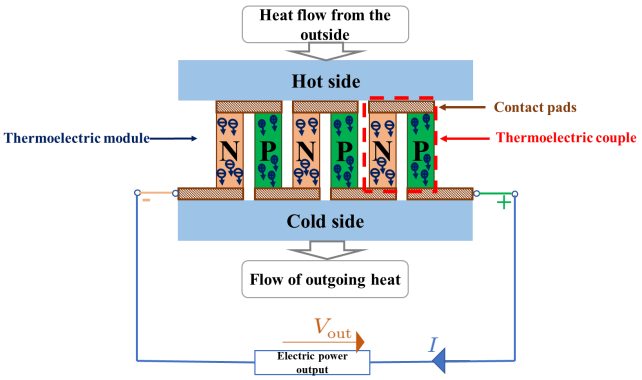


Fig. 3. Schematic of a basic thermoelectric generator.

3.1. Heat-to-electricity conversion efficiency of TEGs

The efficiency of thermoelectric generators depends on the material qualities of the individual legs, as well as geometrical factors, and the influence of module performance.[18] The efficiency of the thermoelectric material for each single thermocouple (connected P- and N-leg) must be evaluated to evaluate device performance. In general, interface thermal and electrical resistances at metal connections are ignored, as although they exist in practice. Efficiency of thermoelectric devices can be calculated by dividing the electric power produced noted P_{e} by the thermic flux crossing hot side defined as Q_{c}.[20] As can be given by the following equation:

$$\eta_{\text{TE}} = \frac{P_{\text{e}}}{Q_{\text{c}}}. \tag{5}$$

The electrical power P_{e} is expressed as a function of the Seebeck effect and the temperature difference ΔT, according to the following equation:

$$P_{\text{e}} = (\alpha_{\text{P}} - \alpha_{\text{N}}) \cdot I \cdot \Delta T. \tag{6}$$

Moreover, the diffusive heat flux φ is calculated by the product of the total thermal conductance κ by the temperature difference ΔT:

$$\varphi = \kappa \cdot \Delta T. \tag{7}$$

In this equation, κ represents the thermal conductance of materials n and p placed in parallel. As for the absorbed thermal power Q_{c}, it is the resultant of the sum of the heat flux and of the Seebeck effect

$$Q_{\text{c}} = (\alpha_{\text{P}} - \alpha_{\text{N}}) \cdot I \cdot T_{\text{hot side}} + \kappa \cdot \Delta T. \tag{8}$$

As a result, by ignoring the contact resistances at the hot and cold junctions in front of the total leg resistances, we eventually obtain the efficiency expression

$$\eta_{\mathrm{TE}} = \frac{(\alpha_{\mathrm{P}} - \alpha_{\mathrm{N}}) \cdot I \cdot \Delta T}{(\alpha_{\mathrm{P}} - \alpha_{\mathrm{N}}) \cdot I \cdot T_{\text{hot side}} + \kappa \cdot \Delta T}. \tag{9}$$

On the other hand, maximal efficiency may be expressed as follows:

$$\eta_{\mathrm{TE}} = \eta_{\mathrm{c}} \cdot \eta_{\mathrm{th}}, \tag{10}$$

where η_{c} and η_{th} represent the Carnot efficiency and the thermoelectric system efficiency, respectively, the Carnot efficiency η_{c} can be calculated using the following formula:

$$\eta_{\mathrm{c}} = \frac{T_{\text{hot side}} - T_{\text{cold side}}}{T_{\text{hot side}}}. \tag{11}$$

The efficiency η_{th} of a thermoelectric system may be estimated by taking into account the following assumptions.

(i) The thermoelectric properties of the materials are constant.

(ii) The temperature on each side of the module is uniform.

(iii) All the heat flow from the hot source to the cold source passes through the thermoelectric materials (parasitic resistances and contact resistances are neglected).

(iv) The electrical contacts between the thermoelectric materials are assumed to be perfect

$$\eta_{\mathrm{th}} = \frac{\dfrac{m}{m+1}}{1 + \dfrac{m+1}{Z \cdot T_{\text{hot side}}} - \dfrac{\Delta T}{2 \cdot T_{\text{hot side}} \cdot (m+1)}}, \tag{12}$$

where ΔT is the temperature difference between the hot and cold side of the module, $T_{\text{hot side}}$ being the temperature of the module on the hot side, m being the ratio of the electrical load resistance to the internal electrical resistance of the thermoelectric module. The figure of merit of the thermoelectric material, Z (K^{-1}) is expressed as follows:

$$Z = \frac{(\alpha_{\mathrm{P}} - \alpha_{\mathrm{N}})}{(\kappa_{\mathrm{P}}\rho_{\mathrm{P}})^{1/2} + (\kappa_{\mathrm{N}}\rho_{\mathrm{N}})^{1/2}}, \tag{13}$$

where κ_{N} and κ_{P} respectively represent the thermal conductivities of thermoelectric materials doped n and p, ρ_{N} and ρ_{P} are the electrical resistivities of the n and p doped thermoelectric materials, respectively.

The properties of these materials change dramatically with temperature, particularly in thermoelectric generation, where the temperature differential between the two sides of the module is critical. As a result, the expression for this yield should be utilized with caution. Nonetheless, we can determine the highest efficiency achievable for m_{opt}, which is expressed as follows:[21]

$$\eta_{\mathrm{TE}_{\max}} = \frac{P_{\mathrm{e}}}{Q_{\mathrm{c}}} = \frac{\Delta T}{T_{\text{hot side}}} \cdot \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_{\text{cold side}}}{T_{\text{hot side}}}},$$

$$m_{\mathrm{opt}} = \sqrt{1+ZT}. \tag{14}$$

Despite the simplicity of the assumptions made above, this formula gives a very good estimate of the efficiency of a TEG. We notice that this formula includes the dimensionless factor of merit ZT and its influence on the efficiency is important.

The maximum efficiency is the product of the Carnot efficiency, and η_{th} taking into account the physical properties of the thermoelements.

The current state of material research allows us to expect for a short-term efficiency of conversion of thermal energy into electrical energy of 10% for temperature differences on the scale of 300 K. The poor efficiency of thermoelectric generators limits their use. The development of thermoelectric generators is hampered by three major obstacles: thermoelectric materials, the creation of optimal thermoelectric modules, and the integration of the modules in systems in order to produce efficient thermoelectric generators.[22]

3.2. Heat exchanger

Even though they are not directly engaged in the conversion of thermal energy to electricity, heat exchangers are critical components of a thermoelectric generator. In fact, they are able to bring heat into or out of the module. The incorrect selection of a single exchanger might lower the overall performance of the generator. Several studies have demonstrated an interest in improving them, primarily by lowering their heat resistance.[23–25] For example, states that for a given volume, a short and broad exchanger is preferable to a long and narrow one.[23] However, lowering a heat exchanger's thermal resistance is frequently accompanied by an increase in space requirements or pressure dips in the hydraulic circuits. A thermoelectric generator is built by connecting thermoelectric modules to exchangers.

4. Types of thermoelectric generators

In this section we will represent different types of a thermoelectric generators from various perspectives such as design, material of composition, and some fabrication methods.

4.1. Thermoelectric generators design

The basic design concept of thermoelectric generators is to provide a flow channel that goes through the effective geometry of each thermocouple, resulting in a temperature differential between its terminals. The thermoelectric generators cited in the literature are classified into three main classes according to their topologies. TEGs may be built in three different ways, depending on how the thermocouples are positioned on the substrate in respect to the heat flow direction.

(i) Type 1. Lateral/lateral design — generators with lateral heat flow, and laterally constructed thermocouples arrangement.

(ii) Type 2. Vertical/lateral design — vertical heat flow generators created by the assembly or arrangement of laterally manufactured thermocouples.

(iii) Type 3. Vertical/vertical design — vertical heat flow generators and vertically constructed thermocouples.

The first TEG type is mainly distinguished by the arrangement of the thermocouples with a planar configuration using a planar thermopile, a set of TCs in series (Fig. 4(a)). The thermocouples can be printed, patterned, or deposited on the substrate surface in this design. The key advantage of this technology is its ability to alter the thickness and length of each thermocouple arm, as well as its compatibility for thin film deposition, which allows for thinner and longer thermocouples than other varieties.[26–29] Furthermore, by utilizing longer TCs arms, this configuration raises the thermal resistance of the thermoelements compared to other TEGs designs, resulting in an increased temperature gradient along these latter and, finally, a rising output voltage.

The vertical TEG, the second TEG design in Fig. 4(b), consists of TCs stacked vertically between the heat source and the heat sink.[30] As a result, heat flows vertically along the thermoelement arms and surfaces. This configuration is comparable to the Peltier-based refrigeration module. This type of TEGs has the highest integration density and is the most marketed because its ease of use, high TCs integration, and high output voltage.[31]

The third TEG design, known as mixed, is made up of TCs positioned laterally on the substrate, with heat flowing vertically (Fig. 4(c)). Vertical heat transmission is achieved by incorporating micro-cavities into the substrate underneath the thermocouple arms. The second and third TEG designs should have two additional plates/substrates positioned above and beyond the module's hot and cold sides.[32] The thermal conductivity of the substrate will impact the temperature differential of the module in this instance, especially if it is substantially lower than that of thermocouples. The temperature differential between the TC arms will be reduced as a result.

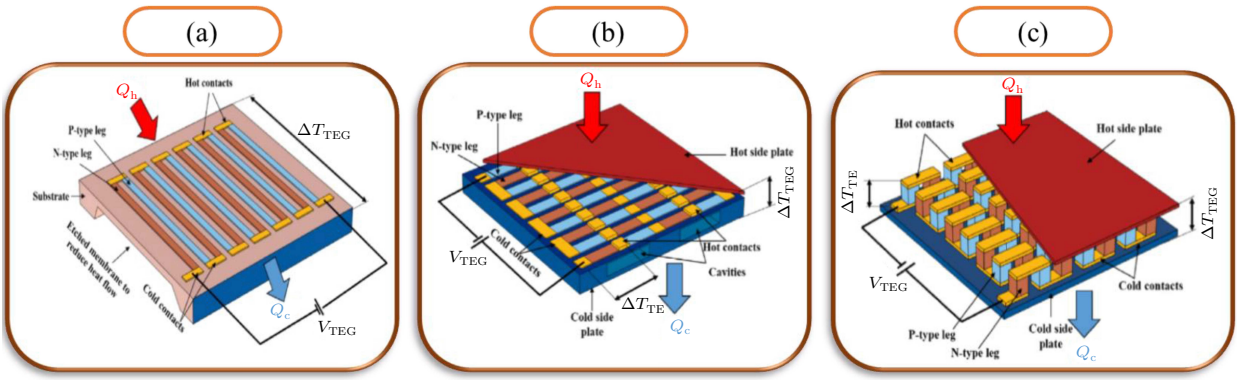


Fig. 4. Different design of TEG. (a) Lateral/lateral. (b) Lateral/vertical. (c) Vertical/vertical.[33]

4.2. Design of a thermoelectric module

Finding a TE material with a high ZT is the primary priority when creating thermoelectric devices for any application. Nevertheless, this is only the first step of TEM construction, turning these thermoelectric materials into devices is the next major obstacle. Some of the critical technical criteria to maximize a TEM's performance include conditions as represented in the Fig. 5.

Geometrical parameters of the thermoelectric module play a very important role in optimizing a TEG. As a typical thermoelectric module is made up of many thermocouples with N and P type legs that are electrically connected in series by high electrical contact pads while functioning thermally in parallel. These thermocouples are protected by ceramic electrical insulators and strong thermal conductivity. This is not, however, the only way to set a thermoelectric module. Additional design structures can be used to increase performance and/or ideally tailor the forms for the appropriate

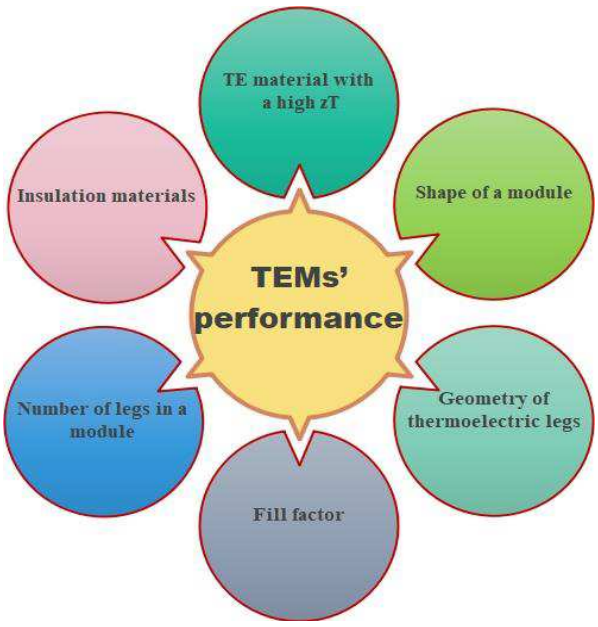


Fig. 5. Criteria dependence of a thermoelectric module.

applications. Figure 6 represents a various structure of TEMs such as conventional,[34] cylindrical,[35] annular,[36] cascaded annular with single stage and two stages.[37] Each structure of a TEM can affect the performance of a thermoelectric generator. Moreover, the electrical resistance and heat transfer of the module are extremely reliant also to the geometrical factors such as leg length, cross-sectional area of a leg, and the number of unicouples in a module.[38]

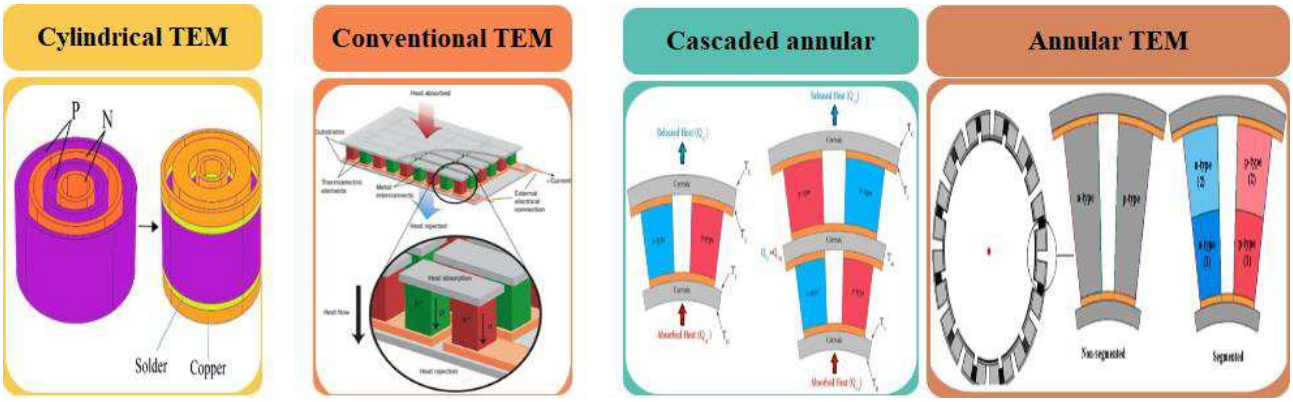


Fig. 6. Representation of some types of TEMs. Cylindrical,[35] conventional,[34] cascaded annular,[37] and annular.[36]

4.3. Thermoelectric generator architecture

Because of the different shapes of the heat recovery surface in contact, several TEG topologies are used. TEG's architecture has a significant impact on their electrical, thermal, and power generating properties. In terms of economic concerns, the fundamental goals of any TEG architecture are to minimize heat loss and contact thermal resistance. TEGs are categorised as fllows based on their architecture.

4.3.1. Flexible TEG

With the introduction of flexible power electronics and wearable sensors, there is a significant need for flexible sources of power for applications such as device powering and monitoring biomechanical activities. The TEGs with flexible architectures give this flexibility without sacrificing efficiency compared to rigid TEGs. Instead of traditional subtractive manufacturing, flexible TEGs use new polymers and composites and are manufactured using innovative manufacturing processes such as additive manufacturing, printing, and thermal spraying.[39,40] Examples of flexible wearable device based flexible thermoelectric generator are represented in the Fig. 7.

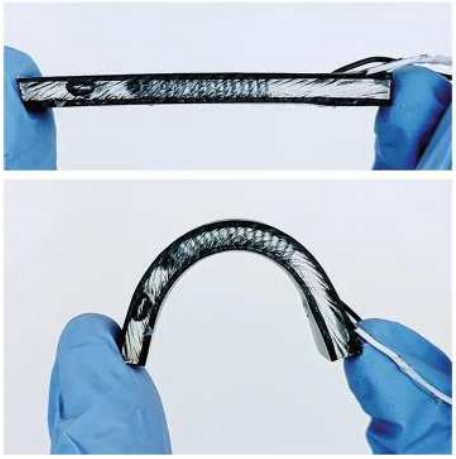


Fig. 7. Example of the flexible wearable device based thermoelectric generator.[41]

4.3.2. TEG with cylindrical bulk structure

A cylindrical form is another proposed design for bulk TEGs, as shown in Fig. 8.[42,43] This design of cylindrical bulk TEGs is suitable for applications where the heat flow is in the radical direction, like as oil pipelines, cooling channels for power station transformers, car exhaust pipes, and so forth.[42] Schmitz *et al.* manufactured tubular PbTe modules experimentally using a current-assisted sintering technique and specifically built sintering molds.[44] In 2015, a firm called Gentherm created prototypes of cylindrical TE modules and used them to improve vehicle power efficiency and an output power of 30 W was achieved for the individual module under ideal conditions.[45] Zhang *et al.*[46] developed an optimized geometry of 72 pairs that were tightly attached to the heat exchanger surface (Fig. 8(c)). The cylindrical structure and large heat transfer area improve heat transfer in the annular TEG's hot and cold ends. Furthermore, they have superior power generation capability, making them a more suitable prospect for applications such as solar energy, space, automobiles, and many others.

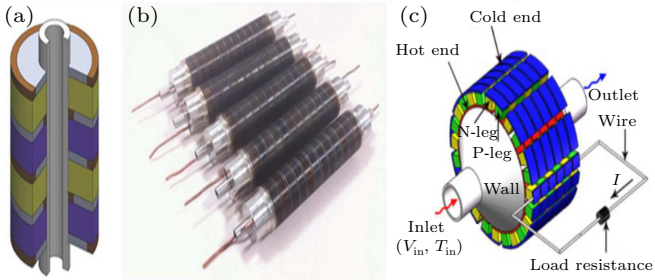


Fig. 8. TE devices with cylindrical shapes.[47] Annular thermoelectric generator (ATEG).[46]

4.3.3. Bulk flat TEG structure

Architecture with a flat mass TEGs are commonly used in high-power production to take advantage of the longitudinal Seebeck effect.[48] The electrical and thermal currents flow parallel in the flat bulk TEGs, which are generally cuboid in form. A powder processing or sintering procedure is used to create flat bulk TEGs with alternating legs of P-type and N-type TEMs. Several studies and efforts have been made to improve the performance of flat bulk TEGs using geometric parameters and TE leg configuration.[49–51]

4.3.4. TEG with thin-film structure

Due to the high heat flow, thin-film TEGs are often constructed in the thickness range of a few micrometres, allowing for large densities of cooling power. Electrochemical deposition has been established as a more viable and cost-effective way of fabricating thin-film TEGs than that of sputtering. Thin film thermoelectric generators can also have several configurations.

(i) Geometries similar to solid modules with the thermoelectric legs as thin films.[52]

(ii) Planar geometry.[53]

4.4. Thermoelectric materials

4.4.1. Traditional materials

The so-called traditional materials are still utilized in modern technologies, such as refrigeration and power generation. Despite being discovered some decades ago (1950–1960), the materials addressed in this section are currently being investigated with the goal of better enhancing their thermoelectric characteristics utilizing novel synthesis procedures or replacement elements that had not been previously explored. Bismuth–antimony alloys, bismuth-lead telluride compounds, and silicon–germanium alloys are the most common of these materials. They are categorised based on the ideal working temperature range. These materials can be classified according to their optimum operating temperature range. The evolution of conventional thermoelectric materials as a function of temperature can be classified according to their optimal operating temperature range as follows.

(i) Bi_2Te_3 and its derivatives $(Bi, Sb)_2$ $(Te, Se)_3$ (200 K–450 K).

(ii) PbTe and its derivatives (450 K–800 K).

(iii) TAGS compounds (tellurium–antimony–germanium–silver).

(iv) Si–Ge alloys (1000 K–1300 K).

4.4.2. Advanced materials

Because of environmental and energy concerns, there has a growth interest in thermoelectricity since 1995. New theories and concepts are suggested in the goal of discovering materials with a ZT factor greater than one. Two paths of investigation have been pursued: the discovery of novel materials and the investigation of low-dimensional systems, particularly nano-structured materials. The first axis is focused on open or complex crystal structures that has phonon glass electron crystal (PGEC) characteristics.[54] Slack suggested this hypothesis in 1997.[55] The goal is to develop a material with the thermal conductivity of a glass and the electrical characteristics of a semiconductor material with great mobility. Several families of materials have been investigated in this context, and it is impossible to describe them all. Several reviews can be found herein for further information.[56–62] Among the most important are cage materials such as skutterudites and clathrates, for which P- and N-type materials with ZT larger than or equal to 1 at moderate temperatures have been found.

A large number of studies have also been done on complicated crystal structures, notably Zintl phases, where various compounds from this family, such as Zn_4Sb_3[63,64] or $Yb_{14}MnSb_{11}$,[65] has exhibited strong P-type characteristics. Semi-Heusler compounds have also demonstrated good performance for both N- and P-types, indicating that they might be developed for applications at intermediate temperatures.[66] Silicides have also received a lot of attention, with promising findings in N-type Mg_2Si.[67,68] Other material families have lately been investigated and evaluated (N-La_3–$x$$Te_4$[69,70]). Promising results of thermoelectric performance of many conductive polymers such as (PEDOT/PSS) and others are cited elsewhere.[71–73] Sulfides have also recently received a lot of attention, and fascinating thermoelectric capabilities have been discovered in tetrahedrites and colusites.[74–76] Tin chalcogenides (e.g., SnTe and SnSe) have also piqued the curiosity of researchers, despite disagreements concerning about SnSe's extraordinary thermoelectric properties ($ZT >$ 2.5 around 800 K).

The second axis is concerned with low-dimensional systems like superlattices, wires, and quantum boxes. These structures are intriguing because their density of states (DOS) is higher than in a 3D structure. Indeed, the high energy changes of their DOS can be used to boost thermoelectric power. Furthermore, because the size of the particles may be changed, these structures have additional degrees of freedom to vary the electrical characteristics. Additional phonon scattering at the surfaces may also help to lower thermal conductivity. Finally, if a material is intriguing in 3D form, the theory predicts that its thermoelectric performance will be even greater when constructed as a 2D quantum well, 1D nanowires, and 0D nanoplots. The goal is to explore if it is feasible to reduce lattice thermal conductivity in a bulk material

composed of nano-sized particles or containing nano-objects inside the matrix. Intensive study has been undertaken in this area, with encouraging findings gained on numerous families of materials (conventional or advanced) as a result of thermal property deterioration.[77]

4.4.3. Flexible polymer composite for thermoelectric

In this section, we will discuss representative insulating polymers that are widely used for flexible thermoelectric (TE) based composites. We will also discuss shortly the advantages and basic TE performance of composites with these polymers. Thus, we will focus on the latest research progress in this area.

(i) Cellulose.

In general, cellulose is a polysaccharide composed of a linear chain of D-glucose (14) units connected together. It is tasteless and odorless, and it is insoluble in water and most organic solvents. It is a hydrophilic substance with strong intermolecular and intramolecular hydrogen bonds, as well as Van der Waals forces, making it difficult to dissolve.[78] Cellulose offers biocompatibility, biodegradability, renewability, strong mechanical strength, environmental friendliness, and is one of the safest materials on the planet.[79] This renewable, sustainable, and ecologically friendly material now receive a lot of attention from academics and industries as an alternative to several non-degradable synthetic materials.

Cheng *et al.* developed a flexible cellulose-based TE sponge (CP : PP sponge) by electrostatically attaching poly (3,4-ethylenedioxythiophene) : poly (styrene sulfonate) (PEDOT : PSS) to cellulose sponges cross-linked with branched polyethyleneimine (CP sponge). The adsorption of PEDOT : PSS on the CP sponge was validated using x-ray photoelectron spectroscopy (XPS). The 3D structures, which are made up of thin sheets and are typical of cellulose sponges, were preserved in the CP : PP sponges. These CP : PP sponges demonstrated reasonable piezoresistive properties as well as outstanding flexibility.[80]

Dong *et al.* developed a simple vacuum filtering process for modifying cellulose paper using inorganic TE powders, resulting in modified paper with good thermoelectric characteristics. Paper-based flexible TE generators (PTGs) are created by linking the modified paper to copper foils. At a temperature differential of 50 K, the PTG created with three units of P–N modules may provide an output voltage of 41.2 mV. Based on this revised work, a thermal sensor that responds to heat sources such as fingers with a quick reaction time of 0.25 s is proposed. This research provides a potential technique for easy PTG manufacturing, opening the path for the commercialization of self-powered wearable electronics (Fig. 9).

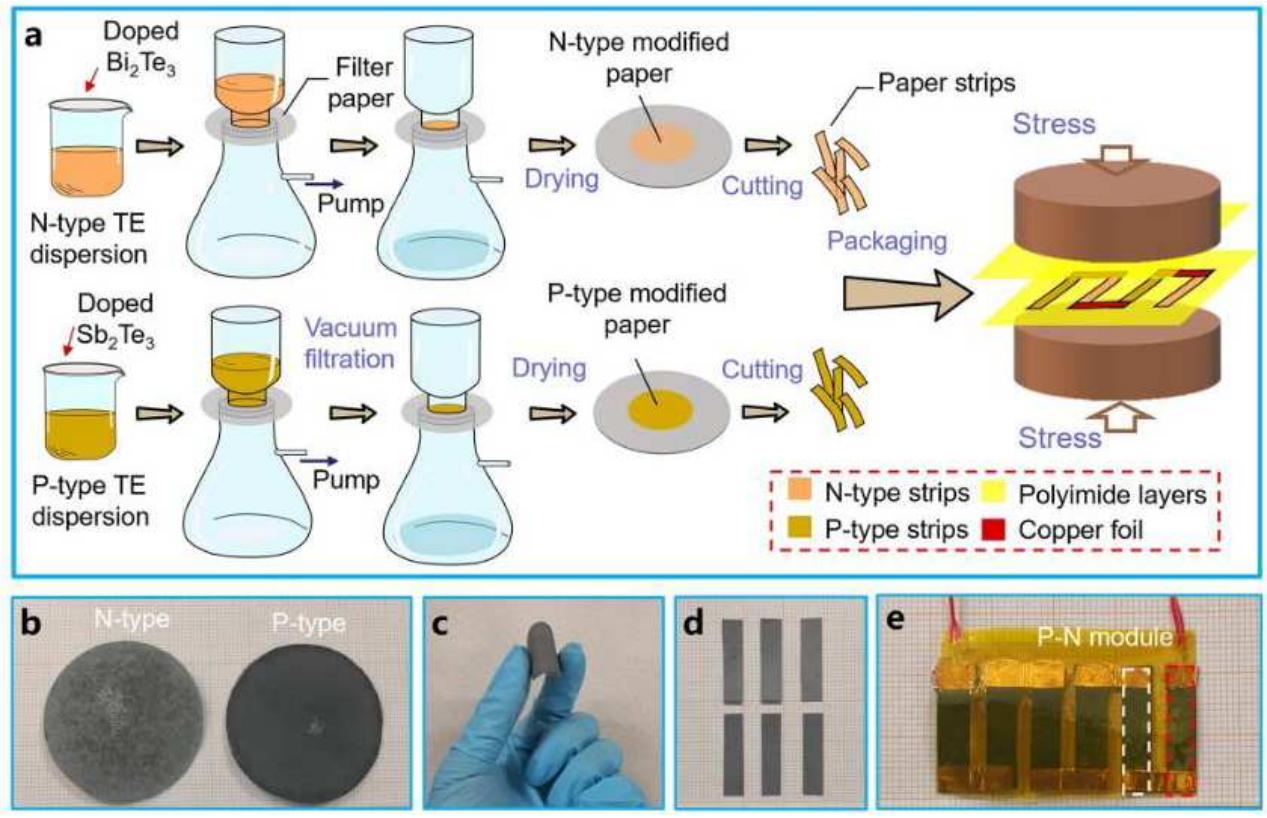


Fig. 9. (a) Schematic diagram of the fabrication process for PTGs. The N- and P-type modified papers are prepared through the vacuum filtration method, cut into small strips and connected with copper foil in an alternating sequence. (b)–(e) Photographs of the complete modified papers obtained by the vacuum filtration method (b), displaying their high flexibility (c), the small 5 mm × 20 mm strips (d), and the PTG with three units of P–N modules (e). The smallest grid point of the background grid paper represents 1 mm.[81]

(ii) Chitosan.

Chitosan is a cationic polymer derived from the deacetylation of chitin, the second most abundant natural polysaccharide in biomass after cellulose.[82] Chitin is a structural substance found in the endoskeletons of arthropods (such as insects, shrimp, and crabs) and cephalopods (i.e., squids, cuttlefishes). Chitosan is a natural polymer with unique features such as biocompatibility, biodegradability, antibacterial capability, and mucoadhesivity, making it an ideal choice for biomedical or cosmetic applications.

To optimize the thermoelectric properties of the composite films, Eunhwa Jang *et al.* manufactured thermoelectric composite thick films (Fig. 10) with two different mesh sizes of N-type bismuth particles, different binder to thermoelectric material weight ratios, and two different pressures, 200 MPa and 300 MPa. The first time chitosan was utilized in this technique, it was dissolved in dimethyl sulfoxide with less than 0.2 wt% chitosan and was adequate to generate TE inks and composite films.[83]

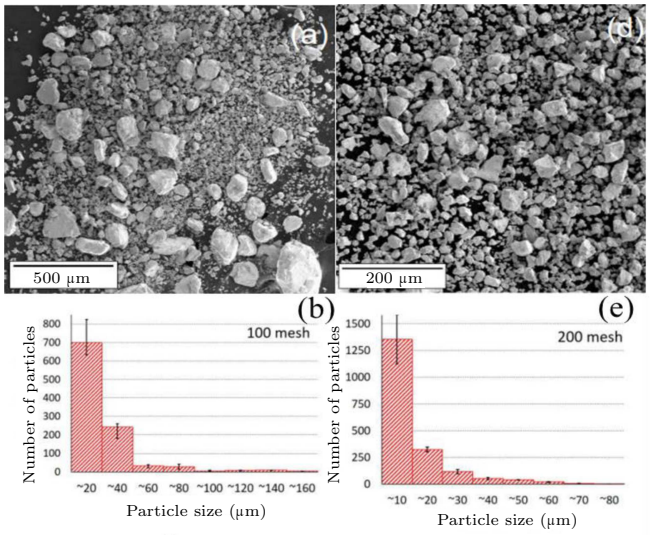


Fig. 10. SEM images of (a) 100-mesh bismuth particles, (d) 200-mesh bismuth particles and particle size distribution of (e) 100-mesh and (f) 200-mesh.[83]

4.4.4. Material selection criteria

The improvement of the dimensionless figure of merit represents the key condition to optimize thermoelectric materials. Unfortunately, the different transport properties involved in the definition of the ZT factor do not vary independently. It is indeed obvious that the combination of low thermal conductivity (as in the case of glass) and high electrical conductivity (as in the case of metal) in the same material is a formidable challenge because these two transport properties appear antagonistic. These observations have been taken up in the criteria proposed by Slack,[54] this suggests that a suitable thermoelectric material will exhibit PGEC (phonon-glass and electron crystal) behavior. Furthermore, a good thermoelectric material must have strong mechanical strength and thermal stability so that it does not degrade throughout its use in a module.

To optimize the thermoelectric parameters of a material from microscopic point of view, several selection criteria have been established empirically by examining the performance of several classes of materials. Moreover, previous studies by Goodman,[84] Ioffe *et al.*,[85] Slack,[86] and Goldsmid[87] have resulted in a list of characteristics that serve as a guide for the search for new materials.

(i) Obtain a charge carrier concentration between 10^{18} cm^{-3} and 10^{21} cm^{-3}.

(ii) Have a bandgap width between 5 K_BT and 10 K_BT (K_B is Boltzmann constant), for a working temperature T.

(iii) Decrease the lattice thermal conductivity with the use of high atomic mass, large mesh, multi-element compounds with low Debye temperature.

(iv) To optimize thermoelectric power, prefer a high effective mass of charge carriers and a substantial variance in the density of states at the Fermi level.

(v) Optimize the ratio μ/κ_L (intrinsic mobility of charge carriers/lattice thermal conductivity) by realizing solid solutions, for which the increase in disorder induces significant phonon scattering through the phenomenon of mass or charge fluctuation in the lattice.

(vi) Improve charge carrier mobility and their effective mass such that semiconductors with high effective mass, high mobility, and low lattice thermal conductivity are the best candidates for thermoelectric applications.

5. TEG fabrication techniques

The earliest realized generators fall under the type of so-called huge or massif generators are fabricated using the steps shown in the Fig. 11. Recent deposition and microfabrication methods have enabled the production of tiny generators in thin layers. Because of advancements in microfabrication processes, thermoelectric generators with dimensions substantially smaller than those of huge generators may now be realized.[88,89] This technology allows for the target of applications using increasingly tiny objects. It also offers the benefit of integrating a large number of P–N semiconductor couples. A bulk generator contains a few tens of pairs of P–N junctions per square centimeter on average, but a thin film generator may integrate over a hundred pairs per square millimeter.[90] As a result, this form of TEG generates usable voltages from relatively minor temperature gradients. On the other side, the huge number of P–N junction pairs raises the generator's electrical resistance, limiting the amount of power generated. For example, a temperature gradient of at least 20 °C is required for a bulk generator to create an open-circuit voltage of 1 V, whereas a temperature gradient of 8 °C produces the same open-circuit voltage for a thin-film generator.[91]

Table 1. Summary of TEGs technologies fabrication.

Technique of fabrication	TEG material		TEG type	TEG performance	Reference
	N-type	P-type			
Screen printing	$Bi_2Te_{2.7}Se_{0.3}$	Sb_2Te_3	planar	$\Delta T = 48$ °C, $P = 150$ μW, $V = 2200$ mV	[101]
Pipette + plate pressing	$Bi_2Se_{0.3}Te_{2.7}$	$Bi_{0.5}Sb_{1.5}Te_3$	vertical	$\Delta T = 35$ °C, $P = 10$ μW, $V = 8.3$ mV	[102]
3D printing	segmented tri-block $Bi_{0.55}Sb_{1.45}Te_3$, $Bi_{0.5}Sb_{1.5}Te_3$, and $Bi_{0.35}Sb_{1.65}Te_3$		planar	$\Delta T = 236$ °C, $\eta = 8.7\%$	[103]
Inkjet printing	$Bi_2Te_{2.7}Se_{0.3}$	$Sb_{1.5}Bi_{0.5}Te_3$	vertical/lateral	–	[104]
Photolithography + DC sputtering method	N-Ag_2Se	P-Ag_2Te	lateral	$\Delta T = 15$ °C, $P = 106$ mW/cm^2, $V = 1.16$ mV	[105]
Chemical exfoliation	WS_2	$NbSe_2$	flexible TEG	$\Delta T = 60$ °C, $P = 38$ nW	[106]
Magnetron sputtering	Bi_2Te_3	Sb_2Te_3	planar	$\Delta T = 20$ °C, $P = 15.24$ μW	[107]
Screen-printing	poly[Kx(Ni -ett)]/PVDF/DMSO	Te nanowires in PEDOT/PSS	radial TEG	$\Delta T = 45$ °C, $P = 15$ nW/cm^2, $V = 85$ mV	[108]

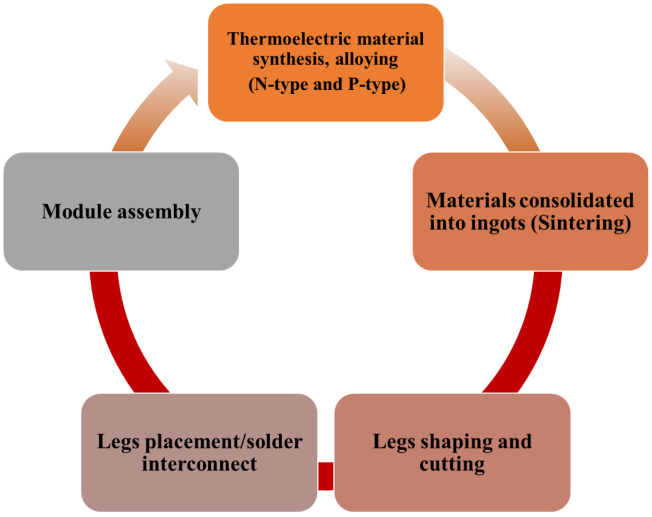


Fig. 11. Bulk thermoelectric generator construction.

Herein, we will represent some fabrication technologies for miniaturized TEG (Table 1) (called also μTEG).

(I) Inkjet printing technology.

In today's society, printing has long been a standard, if not essential, technique. Printing is the process of reproducing an image or text by replicating a pattern onto a substrate. The pattern to be printed must be in a pre-existing physical form in traditional printing procedures (engraving, lithography, etc.). This is inconvenient because each change in the picture to be printed implies a physical change in the pattern. Inkjet printing, on the other hand, works on a completely different premise. It bases on the deposition of a large number of tiny droplets on the substrate in a sequential and progressive manner. The crucial thing is that the drop is created and placed digitally.

Because the pattern to be printed is determined digitally, there is no need for a physical model. This decreases printing costs and time while also allowing for a more flexible and simple printing procedure.

There are two major drop formation mechanisms used:

(i) continuous inkJet (CIJ stands for continuous inkjet).

(ii) drop on demand (DoD).

In both circumstances, the ink is expelled via a hole known as a nozzle. The distinction between these two strategies stems mostly from the drop formation process.

(II) Lithography.

There are two forms of lithography (optical and electronic). The primary distinction between the two is in resolution: electronic lithography (electron beam irradiation) provides a significantly greater resolution, on the order of 5 nm. As for optical lithography, it has a resolution of the order of 1 μm. This technique is used in many works elsewhere.[92–95]

(III) Silicon technology.

This technique used to produce small-scale generators (with diameters ranging from micro- to nanometers). Moreover, this technology can also enable the formation of microcavities in the silicon substrate to minimize heat loss from under hot junctions to improve thermoelectric performance of TEGs.

(IV) 3D printing technique.

3D printing is an additive manufacturing process that involves the addition of material as opposed to subtractive manufacturing techniques such as machining. The 3D printing technique allows for the creation of everyday objects, sepa-

rate parts, or prototypes for testing. The starting point is a computer file that represents the object in three dimensions, divided into sections. These data are sent to a 3D printer, which will create the object by adding consecutive layers.[96] In this regard, 3D printing can provide a significant avenue to control the geometric characteristics of TE legs.[97] However, 3D printing of TE materials and devices is still in its early stages, and the full functionality of TE technology has not yet been utilized.[98,99] Recent advancements in multi-material 3D printing have expanded object designability beyond shape to sophisticated heterogeneous structures.[100]

The following table mentions some fabrication technique of TEGs and their obtained performance.

6. Thermal of the skin and body temperature

The human body remains in a core temperature between 36.5 °C and 37.5 °C.[109] This requires maintaining a balance between the energy generated by metabolism and the heat dissipated into the environment by convection, radiation and evaporation.[110] The core temperature, regulated by the circadian rhythm, changes regularly during the day within the range mentioned above, with a high temperature of 37.5 °C from 10:00 am to 6:00 pm and low temperature of 36.5 °C from 2:00 am to 6:00 am.[111] The core body temperature is normally independent of ambient temperature due to the physiological thermoregulatory systems[112] discussed below.

The thermal conductivity of the skin will be in the range of 0.26 $W{\cdot}m^{-1}{\cdot}K^{-1}$ to 0.3 $W{\cdot}m^{-1}{\cdot}K^{-1}$ according to the temperature and the thickness of the skin.[113] Heat exchange with the environment occurs through the interface of the skin (Fig. 11).[109] The quantity of this heat is regulated by vasodilation and vasoconstriction.[114] As the blood carries heat, minor changes in the blood flow to the skin can greatly influence the amount of heat exchanged with the environment.[115] Figure 11 shows the differences in skin temperature at various locations on the human body in relation to air temperature. The various parts of the human body can be modeled geometrically as concentric cylinders with each layer representing bone, muscle, fat, dermis and epidermis.[116] The first heat exchange model involving isotropic blood permeation was developed by Pennes. Other suggested designs include more factors such as arterial temperature variation during branching, anisotropy of blood perfusion, countercurrent heat exchange, and directional convection.[116]

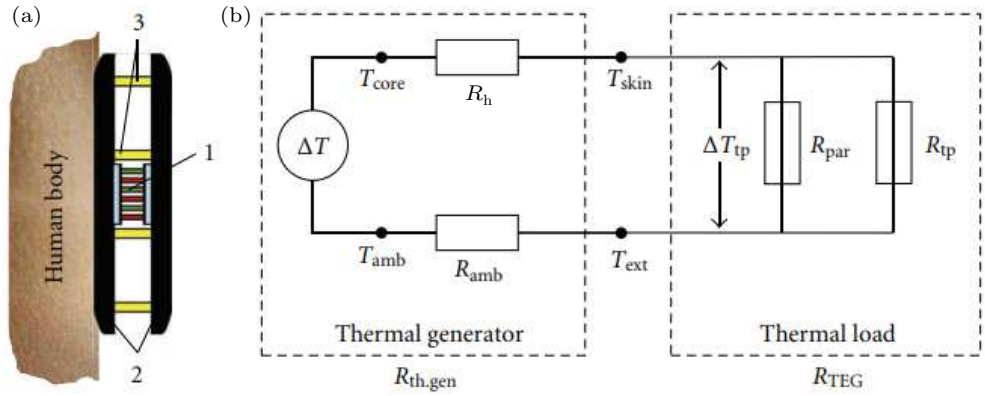


Fig. 12. An illustration of a TEG on the human body and its thermal circuit. In panel (a), 1 is a thermopile between 2 two plates supported by 3 holding and encapsulating elements.[117]

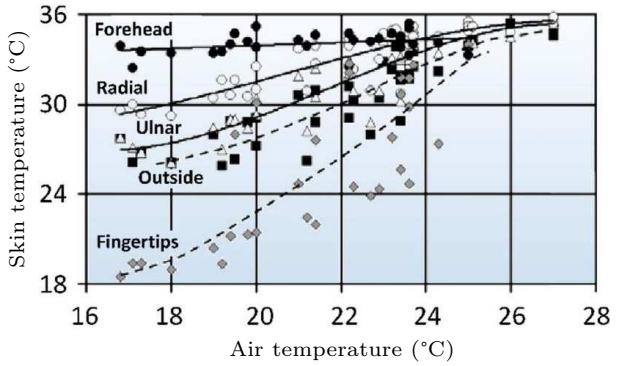


Fig. 13. Variation of skin temperature at wrist, forehead, and fingertips from an ambient temperature of 20 °C.[118]

The mechanism of heat loss can be active or passive. In the case of the human body, a passive system consists of convective and radiative losses, which are beyond the body's control and are dependent on environmental conditions. Convective heat loss can be calculated using Newton's cooling law and depends on the roughness of the skin and the dynamic mechanism of the hair shaft. The radiative losses can be determined using the Stephen–Boltzmann law. An active system, on the other hand, regulates core temperature by modulating blood flow through the skin (Fig. 13), sweating and shivering. In the literature, many mathematical models based on active processes have been developed.

7. Medical applications of thermoelectric generators

An in-depth study of the applications of thermoelectric generators is the main objective of this review. The funda-

mental and basic information and background provided so far will be essential to understand and evaluate the applicability of TEG applications. In addition, in each of the following sections, we have provided basic information on the requirements of each application. We first examine the efficiency of the designs in increasing the performance of these applications, offering a complete analysis and realistic viewpoint on thermoelectric generator applications.

7.1. TEGs for implantable medical devices

TEGs are projected to play a key role in an expanding number of implantable devices. This section reviews the applicability of incorporating a TEG into the human body, the in vitro and in vivo experiments, their results, limitations and prospects. Implantable devices are used as replacements for some of the body's functional organs and are required to be used for the life of the patient. These devices can be supplied either by stocking electricity or by generating it *in situ*. Figure 14 depicts some typical implanted devices.

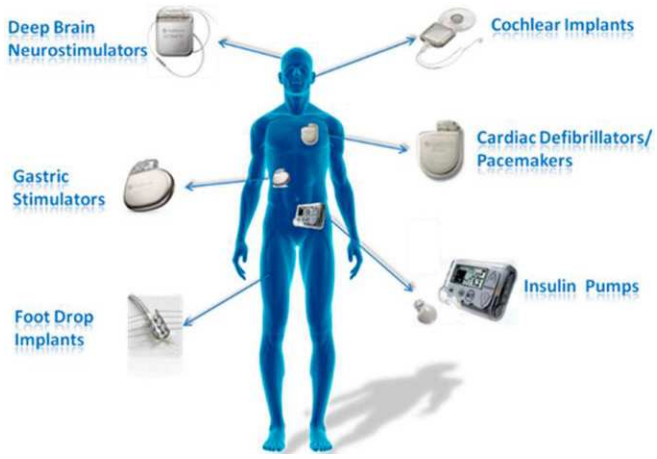


Fig. 14. Common implantable devices.[119]

7.2. Medical and wearable devices

Because body heat is a renewable energy source, it may be used to fully power developing portable and implanted medical devices (IMDs), enabling a wide range of applications such as health monitoring and tracking systems, wearable sports and fitness gadgets, and so on.

In the hospital or at home, these wireless medical devices/sensors may readily monitor safety and physiological conditions, health and developing difficulties, and overall patient analysis. Body heat may be used to power these technological devices by acting as a heat engine. Furthermore, wearable medical devices are not just for patients, but also for healthy people who want to track calories and sleep hours as part of their daily routine. The temperature ranges from 27.1 °C to 35.2 °C depending on bodily activity, location, and ambient circumstances. As a result, the typical temperature difference between the body and the surrounding air is around 13 °C. Wearable medical devices and IMDs require less than 5 mW of electricity to operate.

The importance of low-cost sensors is growing, especially for patient health monitoring. Wearable health monitoring devices provide real-time data to assess a patient's condition over a period of time. When these devices are powered by a patient's bodily motions, significant progress has been achieved, although a solid-state device can transfer data without interruption. These sensors with low sampling rate demand low power, which is made possible by harnessing the energy from the human body. The capability to power these body sensors through wearable TEG is possible due to considerable reductions in sensor size and low-power transmission methods. The wireless transmission power requirements have been reduced drastically to ~ 10 μW.

The human body functions like a thermostat set at 37 °C at the core, while the skin temperature is variable. Heat is generated in the body based on metabolic activity and is dissipated to the surroundings primarily by convection and evaporation. The metabolic activity varies based on the physical activity and age, yet the designed TEG should be able to generate the required power with the minimal metabolic rate. Since wearable TEGs are positioned on the skin, a heat sink or radiator, can be used to enhance the heat flow, however the size is restricted. It is shown that the heat flux from the skin can double for a heat sink the size of a wristwatch. Due to the high thermal resistance of the body, the heat flux from the skin is curtailed, even with an efficient heat sink. Evaluating the heat resistance of the body is a difficult process since it is affected by a variety of factors such as artery proximity, vasodilation, vasoconstriction, and the clothing worn. In addition, attention should be paid to the heat fin design so as not to alter the body heat flow, which may lead to a sensation of discomfort.

Vaithinathan Karthikeyan *et al.* developed a thermoelectric generator (TEG) with configurable geometry to support small thermal impermeability and high temperature gradient (ΔT), which is fundamental for portable and multi-scale energy harvesting applications. As a solution to this issue, we provide a flexible architectural design with an efficient thin-film thermoelectric generator. This design not only reduces the thermal impermeability but also increases the temperature gradient, thereby increasing the energy conversion efficiency (PCE), comparable to that of bulk TEG. Physical vapor deposition of intact tin telluride (P-type) and lead telluride (N-type) thin films over a flexible substrate results in the fabrication of a thermoelectric module with a maximum output power density of 8.4 mW/cm^2. It is demonstrated the performance of P–SnTe/N–PbTe-based TEG as a flexible portable power source for electronic devices, as a tactile thermal sensor for real-time switching, and as a temperature sensor for exoskeleton applications.[120]

8. Thermoelectric generators for automotive waste heat

As the world's population grows, so does the demand for motor vehicles. This increases the number of automobiles on the road, which has an impact on the environment by producing heated, harmful gases. These heated gases are known as waste heat, and they are discharged into the environment. Thermoelectric systems provide major benefits in various domains of application due to their ease of use, acknowledged consistency, particularly due to the absence of mechanical movement that might modify their functioning, and the absence of polluting products following their usage. The thermoelectric generator (TEG) module, which operates on the basis of the Seebeck and Peltier Effect, may be used to transform this waste heat into power. Moreover, only one-third of the potential energy in the fuel is transformed into mechanical energy in a car, and a large percentage of the energy is wasted as heat. Only 25% of the fuel energy required to propel a vehicle is efficient in a conventional internal combustion engine, as illustrated in Fig. 15. Friction dissipates around 5% of the energy. The remaining 70% is lost as heat in the form of exhaust gas and engine coolant. As a result, waste heat recovery is crucial for energy savings and pollution reductions in vehicles. In addition, the quantity of heat released by the exhaust system is extremely high, ranging from 100 °C to 800 °C with a thermal power of up to 10 kW depending on vehicle speed and fuel type.[121] This driven in large part of heat might be regarded as a beneficial source of long-term and adequate energy. Converting the emitted heat will thus be the primary solution for improving engine performance and supplying additional electronic devices such as navigation systems, electronic braking, additional powertrain/body controllers, stability controls, telematics, and collision avoidance systems on conventional and hybrid vehicles. This will also cut air pollution and power expenses.[122]

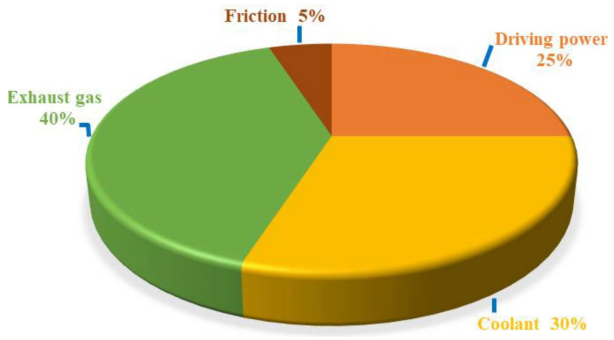


Fig. 15. A typical internal combustion engine's energy flow.

8.1. Automotive exhaust thermoelectric generators

Automotive exhaust thermoelectric generators (AETEGs) are thermoelectric generators (TEGs) that use heat from automotive exhaust. Figure 16 depicts the AETEG structure. An AETEG is generally made up of an exhaust pipe or exhaust heat exchanger, TEGs, and a heat sink. TEGs, which consist of a P- and an N-type legs coupled thermally in parallel and electrically in series (Fig. 16(c)), are sandwiched between exhaust heat exchangers and heat sinks. As seen in Figs. 16(a) and 16(b), liquid and air cooling are commonly used. AETEGs work on a very basic concept.

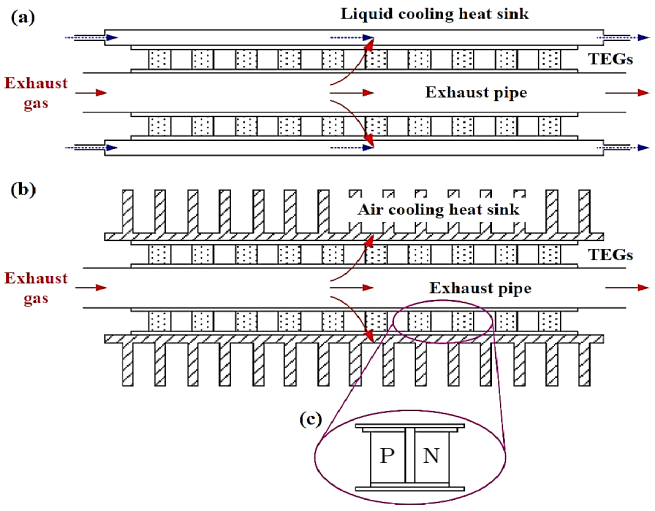


Fig. 16. AETEG constructions: (a) liquid cooling, (b) air cooling, and (c) TEG structure, reprinted with permission from Elsevier for the Ref. [123].

An example for incorporation of an AETEG was shown in a Lincoln MKT with a 3.5-L V-6.[124] Moreover, the Bell solid-state thermoelectric (BSST) team established the largest financed and organized program for high-efficiency thermoelectric waste heat recovery systems for passenger vehicles with the help of the US Department of Energy for BMW automobiles and later for Ford vehicles. The project ran from 2004 to 2012, with a total investment of $10856667 and various development phases.[125] Under steady state circumstances, 605 W power was measured at the design point, and the greatest fuel efficiency improvement was over 1.2%, however, only approximately 450 W was acquired for a speed near the design point under transient conditions, i.e., a dynamic test drive. The average power for the Lincoln MKT-based AETEG was 225 W and 80 W for interstate steady-speed travel and city stop-and-go driving, respectively.

In another study on Chevrolet suburban demonstration vehicle, a number of tasks had been completed, including the study and selection of a demonstration vehicle for a prototype AETEG, the selection of thermoelectric materials, TEG manufacture, AETEG assembly, and testing. The final AETEG, which was cooled by engine coolant, was made up of 42 TEGs, with 24 high temperature skutterudite TEGs upstream and 18 low temperature Bi–Te TEGs downstream. A bypass was created to safeguard the Bi–Te TEGs. The AETEG prototype was displayed in Fig. 17.

Another key source of energy to be tapped in motor vehicles is in the cooling systems, particularly the heat exchanger

on the front of the automobile. In comparison to exhaust gases, there is far less work in progress to energy dissipated by the exchangers in front of the cars, despite the fact that this energy is large. Indeed, the limits imposed by exchangers are even more severe than those found at the exhaust level, because energy recovery devices must be compact, not interfere with exchanger operation, and provide extremely high conversion efficiency. However, in terms of exhaust emissions, it is predicted that a 5% increase in fuel efficiency is feasible with the employment of thermoelectric modules.[126]

As a result, the creation of thermoelectric modules comprised of thin films may be an appropriate alternative. At the working temperatures of the exchangers, thermoelectric materials based on bismuth and tellurium display excellent energy conversion efficiencies, but typical synthesis processes do not appear to be suited for this purpose. Since the early 1990s, a significant new synthesis technique for these materials had been developed: electrochemistry. This enables the synthesis of these materials on films of regulated thickness and composition at ambient temperature and pressure, resulting in substantially cheaper production costs and, possibly, industrial scale manufacturing. For more findings about AETEGs, Table 2 represents a summary result of previous studies on AETEG and their performance.

According to the findings, AETEGs integrating phase change materials should be developed and commercialized for the benefits of safeguarding TEGs, effectively using exhaust heat, lowering fuel consumption and pollutant emissions. However, a number of issues, including low TEG efficiency, inadequate heat extraction ability and non-even temperature distribution of the exhaust side, space constraint, and parasitic penalty, cast doubt on the virtues. That is to say, there is still a long way to go before commercial applications of AETEGs.

Table 2. Summary of publications on TEGs-based exhaust waste heat recovery systems in automobiles.

Type of vehicule	Type of TCs materials	Module specification (length × height × width)	TEG's number	Cooling fluid	Method	Generated power	Reference
–	Bi_2Te_3	350 × 320 × 90 (mm)	12	air	experimental	350 W	[127]
Gasoline engine	Bi_2Te_3	56 × 56 × 5 (mm)	–	engine coolant	simulation	20.6 W	[128]
Gasoline engine	Bi_2Te_3	0.620 × 0.620 × 0.0032 (m)	–	water	theoretical	550 W (max)	[129]
Diesel engine (Nissan YD22)	Bi_2Te_3	–	–	water	experimental & simulation	−1.2 to 24.2 (simulation)	[130]
Gasoline engine	–	40 × 40 × 3.6 (mm)	18	engine coolant	experimental	21.2–98.8	[131]
–	Bi_2Te_3	40 × 40 × 4 (mm)	36	water	experimental	13.08 W	[132]
Diesel automotive	Bi_2Te_3/$(BiSb)_2Te_3$ for low temperature and Mg_2Si/Zn_4Sb_3 for high temperature	50 × 31 × 10 (cm)	–	water	experimental & simulation	1200 W	[133]
Diesel engine	half Heusler alloy	513 × 232 × 190 (mm)	400	water	experimental & simulation	1000 W	[134]

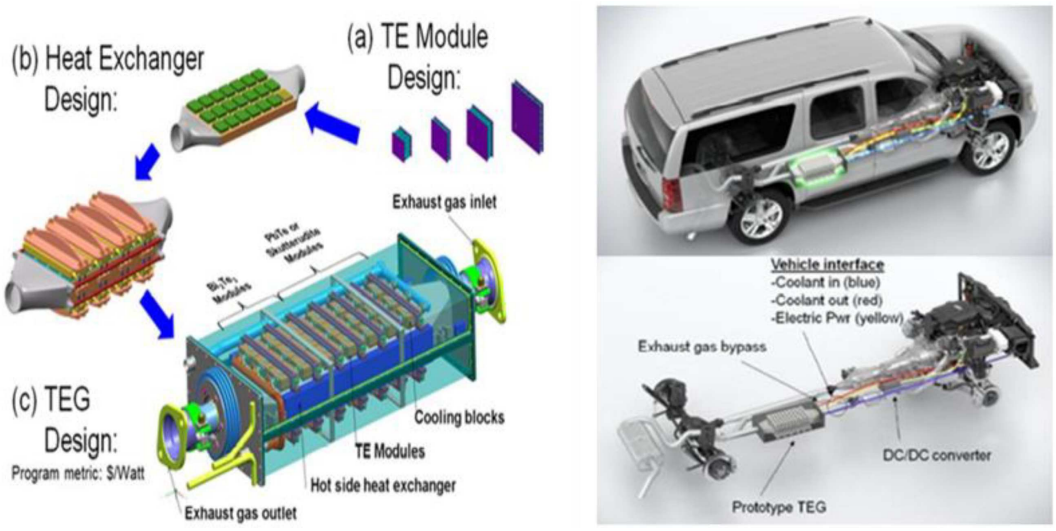


Fig. 17. The TEG design process is divided into steps. This includes optimizing (a) the size and shape of the TE module, (b) the heat exchanger aspect ratio, TE module placement on the heat exchanger, and mechanical components, and (c) the final TEG design based on a two-stage TE module arrangement, thermal and mechanical constraints, and vehicle integration requirements. The program measure ($/Watt) is used to optimize electrical output at the lowest estimated cost. (d) Location of the prototype TEG on the Chevrolet suburban demonstration vehicle.[125]

The advancement of automobile exhaust waste heat recovery requires continuous improvement, with the ultimate goal of maximizing the AETEG's output power while minimizing the impact on the internal combustion engine's original performance with low backpressure. The results of the above quantitative analysis provide a numerical investigation guide for evaluating the performance interaction between AETEG and internal combustion engine, as well as a theoretical insight into the topology optimization of a low-backpressure AETEG with little impact on internal combustion engine in the future.[135]

9. Sensor power supply

The use of energy harvesting systems to power autonomous wireless sensors is critical for the realization of such a sensor for two reasons. First, autonomy reduces the weight and complexity of the entire system because no conventional wiring for data and power transmission is required. Then, using this method, there is no need for regular maintenance checks on the sensors to replace local power sources. On a fighter aircraft, Samson *et al.*[136] tested a wireless autonomous sensor powered by a thermoelectric generator. The thermoelectric generator is connected on one side to the aircraft's hull with a variable temperature of 20 °C to −21 °C and on the other side to a container containing phase change materials. According to their findings, the generator has a conversion efficiency of more than 7%.

10. Aircraft

Sensors and transmitters are increasingly being installed in modern aircraft to improve control, monitoring, and safety. The provision of power to these sensors via power lines would necessitate additional heavy wiring, resulting in increased fuel consumption. Quite possibly the most encouraging methodology is to power such instruments with thermoelectric generators. The utilization of wireless remote sensor network would bring about a decrease in airplane weight and intricacy, as well as a decrease in fuel utilization.

Boeing research & technology estimated that a 0.5% reduction in fuel consumption would result in a $12.075 million reduction in monthly operating costs for US commercial aircrafts and a 0.03% reduction in carbon emissions for US passenger aircrafts, assuming that aircraft contributes approximately 2% to global carbon emissions.[137]

Helicopters have likewise been considered through a review on the practicality of recuperating helicopter exhaust gases utilizing thermoelectric modules. The results of this study show that the electrical energy produced under real operating conditions is significant but currently insufficient, particularly if we take into account the weight/power ratio.[138]

11. Future direction of thermoelectric technology

Thermoelectric applications and energy require various hypothesis and suggestions to improve conversion efficiency and performance in order to obtain current and more sophisticated technologies. As previously described (Subsection 4.4.4), this section represents the current state, challenges, and future direction of thermoelectric technology. The following are some of the possibilities that are useful in thermoelectric power generation.

(i) Theoretical thermoelectric energy change effectiveness is expected to be close to Carnot productivity, but test values are significantly lower. As a result, various advancement components and frameworks for collaborative thermoelectric boundary advancement should be investigated and effectively applied in order to further develop thermoelectric energy transformation productivity.[139]

(ii) Modern synthesis tools, characterization tools, measurement tools, and so on must be investigated in order to use the proper complications and the targeted solution for those complications effectively.[140,141]

(iii) Aside from the growing interest in improving the power factor of thermoelectric materials, the mechanical properties of the new generation of emerging thermoelectric materials and composites are receiving special attention.[142–144] Efforts should also be directed toward developing new designs of flexible thermoelectric devices and investigating potential applications, leveraging advantages such as mechanical flexibility while offsetting disadvantages such as low efficiency.

(iv) With the current development of cell technology and far off sensing systems, the internet of things (IoT) has piqued the interest of many human beings because of its capability to create a big marketplace and its massive effect on human life.[145,146] One of the principals demanding situations in enforcing numerous IoT offerings is the finite energy capability of batteries in sensor nodes. Fixed power sources, inclusive of batteries and gas cells, are bulky and feature a finite quantity of power, in addition to massive drawbacks which includes constrained lifetime, periodic recharging or replacement, and using dangerous chemicals. Therefore, the use of wireless electricity based on thermoelectric energy can be a creative concept which is easily applicable to the applications without the use of non-renewable resources.[147]

(v) Nanotechnology used to generate thermoelectric strength could be a useful utility for powering small and miniature devices. One-dimensional substances, such as nanowires, that interact with thermoelectric substances could be developed as a nanotechnology utility to improve nanodevices.[148]

12. Conclusion

Thermoelectric generator development is now in full force. The possibilities of the application examples shown in this article demonstrate that as soon as heat moves from a hot source to a cold source, the topic of utilizing a thermoelectric generator becomes essential. These generators have matured in high-value-added domains such as space research or difficult-to-reach places that require exceptionally high dependability systems. A lot of academic and industry research are being conducted on mass applications in the automotive area, as well as biomedical devices. In which, we discuss recent advances in the development of flexible thermoelectric materials and devices for wearable thermal energy harvesting applications on the human body such as special-purpose medical sensors, where portable thermoelectric generators may provide benefits over traditional power sources. In addition, automotive domain approximately 40% of the energy produced by an engine is lost in the exhaust pipe. Using this energy in this context would increase engine efficiency, lower fuel consumption and pollutant emissions. Despite the fact that these AETEGs are not yet be commercialized, many researchers have established the viability of AETEGs and achieved significant progress, suggesting that thermoelectric power generation technology is a feasible option for automobile exhaust heat recovery, increasing fuel economy, and decreasing pollutant emissions. By these conclusions, the upcoming large-scale industrial manufacturing of novel materials and modules could help to reduce the cost of thermoelectric generators. The models and tools created by the researchers will aid in the design of generators. As a result, the thermoelectricity sector is predicted to develop fast in the next years and to overtake the others energy conversion technologies.

References

[1] Mustafa Omer A 2008 *Renew. Sust. Energy Rev.* **12** 344
[2] Yang K, Zhang H, Song S, Yang F, Liu H, Zhao G, Zhang J and Yao B 2014 *Energies* **7** 2123
[3] Jouhara H, Khordehgah N, Almahmoud S, Delpech B, Chauhan A and Tassou S A 2018 *Therm. Sci. Eng. Prog.* **6** 268
[4] Ambrosi R, Williams H, Watkinson E, *et al.* 2019 *European radioisotope thermoelectric generators (RTGs) and radioisotope heater units (RHUs) for space science and exploration* (New York: Springer)
[5] Ostrufka A, Borba A, Spengler A and Astronautica T P A 2019 *Experimental evaluation of thermoelectric generators for nanosatellites application* (Amsterdam: Elsevier)
[6] Energy D R A 1991 *Applications of nuclear-powered thermoelectric generators in space* (Amsterdam: Elsevier)
[7] Vazquez J, Sanz-Bobi Ma, Palacios R and Arenas A 2002 *7th Eur. Work. Thermoelectr.* **17**
[8] Tohidi F, Ghazanfari Holagh S and Chitsaz A 2022 *Appl. Therm. Eng.* **201** 117793
[9] Jaziri N, Boughamoura A, Müller J, Mezghani B, Tounsi F and Ismail M 2020 *Energy Rep.* **6** 264
[10] Champier D 2017 *Energy Convers. Manag.* **140** 167
[11] Yang Y, Ma F Y, Lei C H, Liu Y Y and Li J Y 2013 *J. Mech. Phys. Solids* **61** 1768
[12] Vedernikov M V and Iordanishvili E K 1998 *International Conference on Thermoelectrics* pp. 37–42
[13] Snyder G J and Toberer E S 2008 *Nat. Mater.* **7** 105
[14] Slack G 1995 *New Materials and Performance Limits for Thermoelectric Cooling*
[15] Du Y, Shen S Z, Cai K and Casey P S 2012 *Prog. Polym. Sci.* **37** 820
[16] Yu J and Zhao H 2007 *J. Power Sources* **172** 428
[17] Prijic A, Vracar L, Vuckovic D, Milic D and Prijic Z 2015 *IEEE Sens. J.* **15** 337
[18] Owoyele O, Ferguson S and O'Connor B T 2015 *Appl. Energy* **147** 184
[19] De Pasquale G 2013 *Woodhead Publishing Series in Electronic and Optical Materials* pp. 345–400
[20] Chen W H, Lin Y X, Wang X D and Lin Y L 2019 *Appl. Energy* **241** 11
[21] Rowe D M 2006 *Thermoelectrics Handbook: Macro to Nano* (Boca Raton: CRC Press)
[22] Sharma P A and Sugar J D 2014 *Front. Chem.* **2**
[23] Love N D, Szybist J P and Sluder C S 2012 *Appl. Energy* **89** 322
[24] Wang T, Luan W, Wang W and Tu S T 2014 *Appl. Energy* **136** 860
[25] Wang Y, Li S, Zhang Y, Yang X, Deng Y and Su C 2016 *Energy Convers. Manag.* **126** 266
[26] Glatz W and Schwyter E 2009 unpublished
[27] Kao P H, Shih P J, Dai C L and Liu M C 2010 *Fabrication and Characterization of CMOS-MEMS Thermoelectric Micro Generators* **10** 1315
[28] Qing S, Rezania A, Rosendahl L A, Enkeshafi A A and Gou X 2018 *Energy Convers. Manag.* **156** 655
[29] Gierczak M G, Prociów E and Dziedzic A 2020 *Microelectron. Int.* **37** 109
[30] Cho Y H, Park J, Chang N and Kim J 2020 *Energies* **13** 3185
[31] Yuan Z, Ziouche K, Bougrioua Z, Lejeune P, Lasri T and Leclercq D 2015 *Sens. Actuators A Phys.* **221** 67
[32] Yan J, Liao X, Ji S and Zhang S 2019 *J. Microelectromech. Syst.* **28** 1
[33] Jaziri N, Boughamoura A, Müller J, Mezghani B, Tounsi F and Ismail M 2020 *Energy Rep.* **6** 264
[34] Snyder G J and Toberer E S 2008 *Nat. Mater.* **7** 105
[35] Tian M W, Mihardjo L W W, Moria H, Asaadi S, Pourhedayat S, Sadighi Dizaji H and Makatar W H 2021 *Appl. Therm. Eng.* **184** 116274
[36] Tian M W, Mihardjo L W W, Moria H, Asaadi S, Sadighi Dizaji H, Khalilarya S and Nguyen P T 2020 *Appl. Therm. Eng.* **181** 115996
[37] Asaadi S, Khalilarya S and Jafarmadar S 2019 *Appl. Therm. Eng.* **156** 371
[38] Schierning G, Chavez R, Schmechel R, Balke B, Rogl G and Rogl P 2015 *Transl. Mater. Res.* **2** 025001
[39] Tan J, Huang H, Wang D, Qin S, Xiao X, Chen Z, Liu D and Wang L 2020 *J. Mater. Chem. C* **8** 4827
[40] Wang X, Liang L, Lv H, Zhang Y and Chen G 2021 *Nano Energy* **90** 106577
[41] Padmanabhan Ramesh V, Sargolzaeiaval Y, Neumann T, Misra V, Vashaee D, Dickey M D and Ozturk M C 2021 *npj Flex. Electron.* **5** 5
[42] Rowe D M 2005 *Thermoelectrics handbook: macro to nano* (Boca Raton: CRC Press) **80** 1014
[43] Min G and Technology D R S S 2007 *Ring-structured thermoelectric module*
[44] Schmitz A, Stiewe C and Müller E 2013 *J. Electron. Mater.* **42** 1702
[45] Jovovic V 2015 *Thermoelectric Waste Heat Recovery Program for Passenger Vehicles*
[46] Zhang M, Wang J, Tian Y, Zhou Y, Zhang J, Xie H, Wu Z, Li W and Wang Y 2021 *Energy Rep.* **7** 413
[47] He R, Schierning G and Nielsch K 2018 *Adv. Mater. Technol.* **3** 1700256
[48] Uchida K, Ishida M and Kikkawa T 2014 unpublished
[49] Fateh H, Baker C and Hall M 2014 unpublished
[50] You H, Li Z, Shao Y, Yuan X, Liu W, Tang H, Zhang Q, Yan Y and Tang X 2022 *Appl. Therm. Eng.* **202** 117818
[51] Han M and Wee D 2020 *Int. J. Energy Res.* **44** 6049
[52] Kogo G, Xiao B, Danquah S, Lee H, Niyogushima J, Yarbrough K, Candadai A, Marconnet A, Pradhan S K and Bahoura M 2020 *Sci. Rep.* **10** 1
[53] Mizoshiri M, Mikami M, Ozaki K and Kobayashi K 2012 *J. Electron. Mater.* **41** 1713
[54] Slack G A 1995 unpublished
[55] Slack G A 1997 *Materials Research Society Symposium - Proceedings* **478** 47

[56] Wei J, Yang L, Ma Z, Song P, Zhang M, Ma J, Yang F and Wang X 2020 *J. Mater. Sci.* **55** 12642
[57] Liu Z Y, Zhu J L, Tong X, Niu S and Zhao W Y 2020 *J. Adv. Ceram.* **9** 647
[58] Soleimani Z, Zoras S and Ceranic B 2020 unpublished
[59] Ma Z, Wei J, Song P, Zhang M and Yang L 2021 unpublished
[60] Wei J, Yang L, Ma Z, Song P and Zhang M 2020 unpublished
[61] Hasan M N, Wahid H, Nayan N and Mohamed Ali M S 2020 *Int. J. Energy Res.* **44** 6170
[62] Gutiérrez Moreno J J, Cao J, Fronzi M and Assadi M H N 2020 *Mater. Renew. Sustain. Energy* **9**
[63] Zheng J, Chen J, Tang Y, Shen K, He B, Shen L, Ge W, Yang P and Deng S 2022 *J. Solid State Chem.* **306** 122754
[64] Fischer K F F, Bjerg J H, Jørgensen L R and Iversen B B 2021 *ACS Appl. Mater. Interfaces* **13** 45708
[65] Perez C, Wood M, Ricci F and Yu G 2021 unpublished
[66] Jaishi D R, Sharma N, Karki B, Belbase B P, Adhikari R P and Ghimire M P 2021 *AIP Adv.* **11** 025304
[67] Safavi M, Martin N, Aubry E, Linseis V, Billard A and Mohammad A P Y 2021 *J. Mater. Eng. Perform.* **30** 4045
[68] Shiojiri D, Iida T, Kakio H, Yamaguchi M, Hirayama N and Imai Y 2022 *J. Alloy. Compd.* **891** 161968
[69] Drymiotis F, Fleurial J, Bux S, Firdosy S, Start K and Chi I 2018 *Development of high efficiency segmented thermoelectric couples for space applications*
[70] Li J, Liu R, Song Q, Gao Z, Huang H, Zhang Q, Materialia X S A and 2021 unpublished
[71] Bharti M, Singh A, Samanta S and Aswal D K 2018 *Prog. Mater. Sci.* **93** 270
[72] Paulraj I, Yang T S, Wang C H, Liu C J, Liang T F, Chen J L and Wang Y W 2021 *ACS Appl. Mater. Interfaces*
[73] Anno H, Nishinaka T, Hokazono M, Oshima N and Toshima N 2015 *J. Electron. Mater.* **44** 2105
[74] Zhang Y X, Zhu Y K, Feng J and Ge Z H 2022 *J. Alloy. Compd.* **892** 162035
[75] Jose R G, Ng H K, Kumar P, Suwardi A, Zheng M, Asbahi M, Tripathy S, Nandhakumar I, Saifullah M S M and Hippalgaonkar K 2020 *ACS Appl. Mater. Interfaces* **12** 33647
[76] Mulla R, Jones D R and Dunnill C W 2020 *ACS Sustain. Chem. Eng.* **8** 14234
[77] Bux S K, Fleurial J P and Kaner R B 2010 *Chem. Commun.* **46** 8311
[78] Chen X, Chen J, You T, Wang K and Xu F 2015 *Carbohydr. Polym.* **125** 85
[79] Zainal S H, Mohd N H, Suhaili N, Anuar F H, Lazim A M and Othaman R 2021 *J. Mater. Res. Technol.* **10** 935
[80] Cheng H, Du Y, Wang B, Mao Z, Xu H, Zhang L, Zhong Y, Jiang W, Wang L and Sui X 2018 *Chem. Eng. J.* **338** 1
[81] Dong Z, Liu H, Yang X, Fan J, Bi H, Wang C, Zhang Y, Luo C, Chen X and Wu X 2021 *npj Flex. Electron.* **5** 6
[82] Peers S, Montembault A and Ladavière C 2020 *J. Control. Release* **326** 150
[83] Jang E, Banerjee P, Huang J, Holley R, Gaskins J T, Hoque M S B, Hopkins P E and Madan D 2020 *Electronics* **9** 532
[84] Goodman C H L 1958 *J. Phys. Chem. Solids* **6** 305
[85] Ioffe A F 1957 *Semiconductor thermoelements and thermoelectric cooling*
[86] Slack G 1995 *New Materials and Performance Limits for Thermoelectric Cooling* (Boca Raton: CRC Press)
[87] Goldsmid H J and Douglas R W 1954 *Br. J. Appl. Phys.* **5** 386
[88] Böttner H 2002 *International Conference on Thermoelectrics* 2002 pp. 511–8
[89] Böttner H 2005 *International Conference on Thermoelectrics* 2005 pp. 1–8
[90] Nurnus J, Böttner H, Nurnus J, Schubert A and Volkert F 2007 ieeexplore.ieee.org
[91] Siouane S, Jovanovic S and Poure P 2018 *Energies* **11** 1369
[92] Elyamny S, Dimaggio E, Magagna S, Narducci D and Pennelli G 2020 *Nano Lett.* **20** 4748
[93] Elyamny S, Dimaggio E, Magagna S, *et al.* 2020 unpublished
[94] Won Park J, Sun Kim C, Choi H, Jun Kim Y, Soup Lee G, Jin Cho B, Park J W, Kim C S, Choi H, Kim Y J, Lee G S and Cho B J 2020 *Wiley Online Library* **5**
[95] Shimizu Y, Mizoshiri M and Mikami M 2018 unpublished
[96] Farahani R D, Dubé M and Therriault D 2016 *Adv. Mater.* **28** 5794
[97] Kim F, Kwon B, Eom Y, Lee J E, Park S, Jo S, Park S H, Kim B S, Im H J, Lee M H, Min T S, Kim K T, Chae H G, King W P and Son J S 2018 *Nat. Energy* **3** 301
[98] Qiu J, Yan Y, Luo T, Tang K, Yao L, Zhang J, Zhang M, Su X, Tan G, Xie H, Kanatzidis M G, Uher C and Tang X 2019 *Energy Environ. Sci.* **12** 3106
[99] Burton M R, Mehraban S, Beynon D, McGettrick J, Watson T, Lavery N P and Carnie M J 2019 *Adv. Energy Mater.* **9** 1900201
[100] Hardin J O, Ober T J, Valentine A D and Lewis J A 2015 *Adv. Mater.* **27** 3279
[101] Yuan Z, Tang X, Liu Y, Xu Z, Liu K, Li J, Zhang Z and Wang H 2019 *J. Power Sources* **414** 509
[102] Zhao X, Han W, Zhao C, Wang S, Kong F, Ji X, Li Z and Shen X 2019 *ACS Appl. Mater. Interfaces* **11** 10301
[103] Yang S E, Kim F, Ejaz F, Lee G S, Ju H, Choo S, Lee J, Kim G, Jung S H, Ahn S, Chae H G, Kim K T, Kwon B and Son J S 2021 *Nano Energy* **81** 105638
[104] Yang S, Qiu P, Chen L and Shi X 2021 *Small Sci.* **1** 2100005
[105] Yang S, Cho K, Park Y and Kim S 2018 *Nano Energy* **49** 333
[106] Oh J Y, Lee J H, Han S W, Chae S S, Bae E J, Kang Y H, Choi W J, Cho S Y, Lee J O, Baik H K and Lee T I 2016 *Energy Environ. Sci.* **9** 1696
[107] Shen H, Lee H and Han S 2021 *Curr. Appl. Phys.* **22** 6
[108] Boudouris B W, Yee S K, Appl J, Orrill M, LeBlanc S, Gordon M P, Zaia E W, Zhou P, Russ B, Coates N E, Sahu A, Urban J J, Culebras M, de Lima J M M, Gómez C, Cantarero A, Menon A K, Uzunlar E, Wolfe R M, Reynolds J R, Marder S R, Appl P J, Fang H, Popere B C, Thomas E M, Mai C K, Chang W B, Bazan G C, Chabinyc M L, Segalman R A, Meek O, Eng A J and Yee S K 2017 *J. Appl. Polym. Sci.* **134** 44456
[109] Arthur C and Guyton J E H 2006 *Textbook of Medical Physiology*
[110] Gagge A P and Gonzalez R R 1996 *Mechanisms of Heat Exchange: Biophysics and Physiology Comprehensive Physiology* (Hoboken: Wiley) pp. 45–84
[111] Greg K 2007 *Altern. Med. Rev.* **11** 278
[112] Gagge A P, Stolwijk J A J and Hardy J D 1967 *Environ. Res.* **1** 1
[113] Saggin B, Tarabini M and Lanfranchi G 2012 *IEEE Trans. Instrum. Meas.* **61** 489
[114] Kim T K 2017 *J. Mech. Sci. Technol.* **31** 4011
[115] Gagge A P and Nishi Y 1977 *Heat Exchange Between Human Skin Surface and Thermal Environment Comprehensive Physiology* (Hoboken: Wiley) pp. 69–92
[116] Park H, Eom Y, Lee D, Kim J, Kim H, Park G and Kim W 2019 *Energy* **187** 115935
[117] Leonov V 2011 *ISRN Renewabl. Energy* **2011** 1
[118] Leonov R J M V 2007 *Proc. 5th Eur. Conf. Thermoelectr.*
[119] Kumar P M, Babu V J, Subramanian A, Bandla A, Thakor N, Ramakrishna S and Wei H 2019 *Designs* **3** 22
[120] Karthikeyan V, Surjadi J U, Wong J C K, Kannan V, Lam K H, Chen X, Lu Y and Roy V A L 2020 *J. Power Sources* **455** 227983
[121] On J Y I 2005 unpublished
[122] Tang Z, Deng Y and Su C 2015 unpublished
[123] Shen Z G, Tian L L and Liu X 2019 *Energy Convers. Manag.* **195** 1138
[124] Crane D, Lagrandeur J, Jovovic V, Ranalli M, Adldinger M, Poliquin E, Dean J, Kossakovski D, Mazar B and Maranville C 2013 *J. Electron. Mater.* **42** 1582
[125] Meisner G 2011 *Program Final Report - Develop Thermoelectric Technology for Automotive Waste Heat Recovery*
[126] Sivaprahasam D, Harish S, Gopalan R and Sundararajan G 2018 *Bringing Thermoelectricity into Reality*
[127] Kim S K, Won B C, Rhi S H, Kim S H, Yoo J H and Jang J C 2011 *J. Electron. Mater.* **40** 778
[128] Yang H, Shu G, Tian H, Ma X, Chen T and Liu P 2018 *Appl. Therm. Eng.* **144** 628
[129] Brito F P, Alves A, Pires J M, Martins L B, Martins J, Oliveira J, Teixeira J, Goncalves L M and Hall M J 2015 *J. Electron. Mater.* **45** 1846
[130] Pablo F Y, Armas O, Capetillo A and Martínez S 2018 *Appl. Energy* **226** 690
[131] Kim T Y, Kwak J and Kim B W 2018 *Energy Convers. Manag.* **160** 14
[132] Cao Q, Luan W and Wang T 2018 *Appl. Therm. Eng.* **130** 1472

[133] Espinosa N, Lazard M, Aixala L and Scherrer H 2010 *J. Electron. Mater.* **39** 1446
[134] Zhang Y, Cleary M, Wang X, Kempf N, Schoensee L, Yang J, Joshi G and Meda L 2015 *Energy Convers. Manag.* **105** 946
[135] Quan R, Liang W, Quan S, Huang Z, Liu Z, Chang Y and Tan B 2022 *Appl. Therm. Eng.* **216** 119055
[136] Samson D, Kluge M, Becker T and Schmid U 2011 *Sensors Actuators A Phys.* **172** 240
[137] Huang J 2009 *Aerospace and Aircraft Thermoelectric Applications*
[138] Kousksou T, Bédécarrats J P, Champier D, Pignolet P and Brillet C 2011 *J. Power Sources* **196** 4026
[139] Choi J, Dun C, Forsythe C, Gordon M P and Urban J J 2021 pubs.rsc.org
[140] Tzounis L 2019 *Nanomaterials Synthesis: Design, Fabrication and Applications* (Amsterdam: Elsevier) pp. 295–336
[141] Maxa J, Novikov A and Nowottnick M 2018 *EMPC* 2017-21*st European Microelectronics and Packaging Conference and Exhibition* pp. 1–9
[142] Chen Z, Guo X, Zhang F, Shi Q, Tang M and Ang R 2020 *J. Mater. Chem. A* **8** 16790
[143] Chen Z, Wang R, Wang G, Zhou X, Wang Z, Yin C, Hu Q, Zhou B, Tang J and Ang R 2018 *Chin. Phys. B* **27** 047202
[144] Zhong Y, Tang J, Liu H, Chen Z, Lin L, Ren D, Liu B and Ang R 2020 *ACS Appl. Mater. Interfaces*
[145] Haras M and Skotnicki T 2018 *Nano Energy* **54** 461
[146] Zaia E W, Gordon M P, Yuan P and Urban J J 2019 *Adv. Electron. Mater.* **5** 1800823
[147] Wang J, Xiao F and Zhao H 2021 *Renew. Sust. Energy Rev.* **151** 111522
[148] Tiwari S K, Pandey R, Wang N, Kumar V, Sunday O J, Bystrzejewski M, Zhu Y and Mishra Y K 2022 *Adv. Sci.* **9** 2105770