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Review

Thermoelectric generators: A review of applications

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ABSTRACT

In past centuries, men have mainly looked to increase their production of energy in order to develop their industry, means of transport and quality of life. Since the recent energy crisis, researchers and industrials have looked mainly to manage energy in a better way, especially by increasing energy system efficiency. This context explains the growing interest for thermoelectric generators.

Today, thermoelectric generators allow lost thermal energy to be recovered, energy to be produced in extreme environments, electric power to be generated in remote areas and microsensors to be powered. Direct solar thermal energy can also be used to produce electricity.

This review begins with the basic principles of thermoelectricity and a presentation of existing and future materials. Design and optimization of generators are addressed. Finally in this paper, we developed an exhaustive presentation of thermoelectric generation applications covering electricity generation in extreme environments, waste heat recovery in transport and industry, domestic production in developing and developed countries, micro-generation for sensors and microelectronics and solar thermoelectric generators. Many recent applications are presented, as well as the future applications which are currently being studied in research laboratories or in industry. The main purpose of this paper is to clearly demonstrate that, almost anywhere in industry or in domestic uses, it is worth checking whether a TEG can be added whenever heat is moving from a hot source to a cold source.

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1. Introduction and basics

Electricity production is an important issue for our societies. Waste heat is also an important topic. It is in this context that thermoelectric generators (TEGs) are currently taking off. TEGs consist of a set of thermoelectric (TE) modules inserted between two heat exchangers. Each TE module is then composed of several tens to hundreds of pairs of TE couples connected together electrically in series and thermally in parallel, which directly convert a part of the thermal energy that passes through them into electricity.

The advantages of TEGs are numerous:

- direct energy conversion, unlike many heat engines that first convert thermal energy into mechanical energy and then convert this mechanical energy into electricity using an alternator,
- no moving parts and no working fluids inside the TEG, hence no maintenance and no extra costs,
- a long lifespan, especially when working with constant heat sources,
- no scale effect: TEG can be used for micro generation in very limited spaces or to produce kilowatts,
- noiseless operations,
- any working position is possible, making TEGs well suited for embedded systems.

Despite these advantages, for many years TEGs were limited to space applications where their extreme reliability justified their use to provide electricity to the majority of probes sent into space (Voyager, Apollo, Pioneer, Curiosity, etc.). Low efficiency and high cost have been a barrier to their development for more common applications.

Efficiency (defined as the ratio of the electrical energy produced W_{elec} to the thermal energy entering the hot face Qh) of a TE module used as a generator can be approximated by the following relationship [1–3] for an optimal electric load:

$$\eta_{TEmax} = \frac{W_{elec}}{Q_H} = \frac{\Delta T}{T_H} \cdot \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}} \quad \text{with}$$

$$Z = \frac{(\alpha_p - \alpha_n)^2}{\left((\lambda_p.\rho_p)^{1/2} + (\lambda_n.\rho_n)^{1/2}\right)^2}$$

with T_H the temperature of the hot side of the TE modules, T_C the temperature of the cold side of the modules, and $\Delta T = T_H - T_C$ the temperature difference. Z is the factor of merit of the TE materials and can be expressed as a function of the electrical resistivities ρ_p and ρ_n, the thermal conductivities λ_p and λ_n and the Seebeck coefficients α_p and α_n of each of the two materials of the thermocouple. $T = (T_H - T_C)/2$ is the average temperature. ZT, product of the factor of merit by the average temperature is called the dimensionless figure of merit. It is a very convenient way of comparing the properties of materials as it appears in the expression of the efficiency and plays an important role in power maximizing [4].

Currently available TE materials have a ZT of around 1 or less. In the last decades, Bismuth Telluride (Bi2Te3) has been the only material which has been used for industrial thermoelectric modules. For these modules the average value of ZT is between 0.5 and 0.8. Fig. 1 shows that the effective efficiency for industrial applications is a few percent. ZT = 1 is the average value which is expected for the next years. The outlook for laboratories is to develop materials with a ZT of 2 in order to have an efficiency over 10%.

As this low efficiency is an obstacle to development of TEGs, researchers and manufacturers have tried to improve three main issues: improving ZT, increasing the operating range of materials to work with higher temperature differences and, finally, searching for low-cost materials to counteract the negative effect of low efficiency. The results in terms of TE modules will be presented in paragraph 2.

The design and optimization of TEGs is also an important issue and will be addressed briefly in paragraph 3.

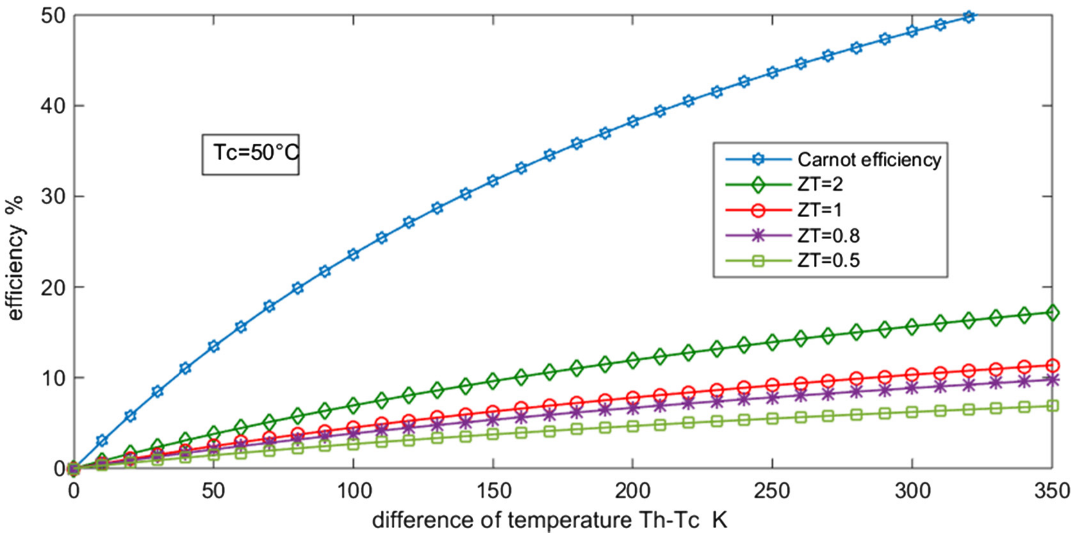

Fig. 1. Typical values of TE efficiency for different values of ZT.

As the different barriers that have blocked industrial development of TEGs are gradually disappearing, an exhaustive presentation of TEG applications is necessary. In 2003, Riffat et al. [5] published a review, but many changes have occurred since this date. More recently in 2014, Zheng [6] presented a review, but only 8 references were dated after 2011. Ahiska [7] also presented a review including 24 references between 2011 and 2014 but the discussion of the applications lacks detail. As the development of TEGs is expanding, a more recent review is required to present the latest applications.

In this paper, the advances in the production of new thermoelectric modules is discussed in Section 2. Section 3 presents the design and optimization of thermoelectric generators. Section 4 provides a classification of TEG applications with a hundred references between 2011 and 2016. The applications described are both in the form of laboratory prototypes and industrial projects or developments. The outlook for these applications thanks to new materials is also discussed.

2. Materials

For many years, the only modules available for industrial applications (with the exception of space) at a reasonable price were Bismuth Telluride modules (Bi_2Te_3). A non-exhaustive list of companies from different continents can be cited: HiZ (USA) [8], Marlow (USA) [9], TECTEG (Canada) [10], Thermonamic (China) [11], Lairdtech [12], KELK previously Komatsu (Japan) [13], QuickOhm (Germany) [14] and Kryothem (Russia) [15]. ZT is approximately 1 at around 50 °C and then decreases at higher temperatures. The maximum operating temperature is between 200 °C and 300 °C depending on the manufacturers. The low abundance of Bismuth and Tellurium [16] in the earth's crust and in the oceans is also a problem for manufacturers. These two points have limited the development of TEG based on Bi_2Te_3. Weight is also a limitation for embedded applications.

Since the beginning of the conquest of space, many other materials with interesting thermoelectric properties have been developed. Few of these materials have been used to make modules and they have been produced only for space applications due to their high development cost: the period of time between discovery of the materials and production of industrial modules is long, although the discovery of all these materials has provided a roadmap for manufacturers and researchers.

For ten years, manufacturer research laboratories have been looking for inexpensive, more environmentally-friendly replacement materials that can be produced commercially in large quantities. This research has been fruitful. In the past few months, new modules have become commercially available or are close to commercialization: half heusler, skutterudites, oxides, magnesium silicides and tetrahedrites.

Recent papers [17,18] have presented the values of the factor of merit ZT of these materials. In the current paper, only those modules that are already available or soon to be marketed are presented and summarized in Table 1.

Half-Heusler modules will be coming soon from Evident Thermolectrics. This company has developed 2 types of modules, product name TEG-HH-8 [19] and product name TEG-HH-15 [20], which can produce respectively up to 7.2 W and 15 W when a temperature gradient of 500 °C is applied (assumes 100 °C cold-side temperature). The hot-side continuous temperature must be maintained below 600 °C with intermittent operation below 700 °C. The size of the modules is 40 mm × 40 mm × 4.9 mm. Thermal cycling performance has been analyzed by the manufacturer: Th cycling between 600 °C and 225 °C with 8 min heating to 600 °C, 10 min hold at 600 °C and 12 min cool down to 225 °C. The results for 1000 thermal cycles show no significant degradation in electrical output power.

At the 34th Annual International Conference on Thermoelectrics in 2015 (ICT2015), the Shanghai Institute of Ceramics presented TEG25, a CoSb3-based skutterudite which can produce up to 25 W when a temperature gradient of 510 °C is applied (assumes 65 °C cold-side temperature). Peak ZT for the N-type (Yb0.3Co4Sb12) is around 1.2, while peak ZT for the P-type (CeFe3-CoSb12) is around 0.75 at T = 800 K. The size of the module is 50 mm × 50 mm × 10 mm and it contains 32 couples of 5 mm × 5 mm × 8 mm.

Tegma [21] is developing skutterudite thermoelectric elements and has developed a reliable bonding technology [22] and high-throughput automated module production processes.

TECTEG MFR markets Calcium/Manganese oxide modules with the references CMO-32-62S and CMO-25-42S [23]. The upper limit of the hot side is 850 °C, but regular temperature is about 800 °C.

Table 1
List of TE modules and their properties.

Manufacturer	Materials	Temperature difference ΔT	Power weight	Status	Maximum temperature	Information, outlook
HiZ, Thermonamic, Lairdtech, Marlow, Komatsu etc.	Bi_2Te_3	300 K	20 W 115 g	€40–€100	300 °C	Scarce (rare earth), toxicity
Evident Thermoelectric	Half-Heusler	500 K	15 W	Coming soon	600 °C	Environmentally-friendly, low cost, availability of raw materials
Shanghai Institute of Ceramics	Skutterudites	510 K	25 W	Coming soon	600 °C	Environmentally-friendly, low cost, availability of raw materials
TEGMA	Skutterudites			s still in development		Environmentally-friendly, low cost, availability of raw materials
TECTEG MFR	Calcium/Manganese oxide	750 K	12.3 W	Available	800 °C	Environmentally-friendly, low cost, availability of raw materials
TECTEG MFR cascade modules	Calcium/Manganese oxides with Bi_2Te_3	435 K	11 W	Available	600 °C	
TECTEG MFR hybrid modules	BiTe–PbTe	320 K	21.7 W	Available	360 °C	Scarce (rare earth), toxicity
Hotblock Onboard	Silicon-based alloy	500 K	3.6 W 6 g	Available	600 °C	Environmentally-friendly, low cost, availability of raw materials
Romny Scientific	Magnesium silicide			Coming soon	600 °C	Low $/Watt target: 1$/W
Alphabet Energy	p-type tetrahedrites n-type magnesium silicide	300 K	9.2 W	Available	600 °C	Tetrahedrite is a naturally-occurring p-type mineral
OTEGO CDT	Organic TEG	Small temperature gradients		Coming soon	130 °C	Environmentally-friendly, low cost, easily scalable

These modules can produce 12.3 W and 7.5 W respectively when a temperature gradient of 750 °C is applied (assumes 50 °C cold-side temperature). The size of the modules is 64.5 mm × 64.5 mm × 8.6 mm and 42 mm × 42 mm respectively. They contain 32 couples and 25 couples respectively. The 2015 price of these modules was around \$360 and \$310. This high price is far from what might be expected once the modules are sold in large quantities. TECTEG also produces cascade modules: high temperature Calcium/Manganese oxides bonded with Bi_2Te_3 on the cold side. These are the first cascade TE modules ever to be commercially available with a hot side of up to 600 °C and a cold side of up to 200 °C. The 2015 price of these modules was around \$560. These modules can produce 11 W when a temperature gradient of 435 °C is applied (assumes 45 °C cold-side temperature). The size is the same as the CMO-32-62S.

Although they are not environmentally friendly, BiTe–PbTe hybrid TE modules are also available from TECTEG. These hybrid TE power modules [24] are designed with high temperature bonding materials that allow them to withstand temperatures of up to 360 °C. These novel TEG modules work best in the 200 °C to 360 °C temperature range and offer superior power output over 260 °C hot side, compared to standard BiTe modules. These modules can produce 21.7 W when a temperature gradient of 320 °C is applied (assumes 30 °C cold-side temperature). The 2015 price of these modules was around \$95.

Hotblock Onboard [25] produces a module (NEMO) made of a silicon-based alloy. It delivers 3.6 W for a hot-side temperature of 580 °C and a cold-side temperature of 80 °C. The dimensions are 20 mm × 24 mm for a thickness of 7 mm. Sample quantities are available now. The 2014 price was around €200 but should decrease considerably due to the low price and large quantity of materials used. These modules have very low weight which offers interesting potential for embedded applications.

Romny Scientific [26] is developing TE modules made of magnesium silicide materials. These are low-cost, abundant raw materials. The aim of this company is to develop low-cost-per-watt modules: the target is \$1/W.

Alphabet Energy [27,28] plans to produce TE modules made of a non-toxic compound: p-type tetrahedrite and n-type magnesium silicide (Mg_2Si) pellets. Tetrahedrite is a naturally-occurring p-type mineral that exhibits a ZT of almost 1 at 720 K. Magnesium Silicide, a non-toxic n-type compound has a ZT of 1.3 at 750 K. This two compounds are compatible. One of the most appealing properties of Mg_2Si is its very low density (i.e. $<2\ g/cm^3$) which will be decisive for transport applications.

General progress and interest in organic materials have contributed to new development for organic thermoelectric materials especially conductive polymers. In laboratory, conducting polymer based on the 3,4-ethylenedioxythiophene monomer (PEDOT) [29] have reached a ZT value of 0.42 (p-type). For the n-type, value of ZT = 0.2 have been obtain with coordination polymers poly[K_x(Ni-ett)] [30], polymers constructed from metal ions and ligands, with metal ions acting as connectors and ligands as linkers. More detailed information about organic TE materials can be found in [31,32].

These materials may be incorporated into new module designs that take advantage of their mechanical properties despite their low thermoelectric properties.

These organic TE materials are limited to low temperature (<130 °C) energy harvesting. They are flexible and they can be printed on very thin foils. These materials are easy to manufacture: printing technology are easily scalable to large areas and this allow easy mass production at potentially low cost. They are non-toxic.

Recently two companies arrived on the market:

- Otego [33] used a derivative of PEDOT and has deposed patents based on the roll-to-roll printing of organic thermoelectric materials. These printed ultrathin foils can be folded to produce a cube of thermoelectric material, or other shapes to suit different applications.
- Cambridge Display Technology (CDT) [34] has presented flexible low-cost organic TE material at Printed Electronics Conference in Berlin, Germany [35].

Printed polymer TE modules can easily be shape to different configurations and first calculations on optimized design have already been done by Aranguren et al. [36].

New organic TEGs are still undergoing research but will probably appear on the market in a few months. Table 1 summarizes the properties of all these modules: the materials used, suitable temperature difference between the two sides of the modules, the maximum power obtained for this difference, availability of the module, the maximum continuous working temperature and some information and outlook.

As can be seen, many mineral TEGs are available or coming soon. Their new properties, such as their operating range, price, weight and non-toxicity, open up interesting prospects for large-scale industrial development.

3. Design and optimization

Industrial use of TE modules requires other elements to form a powerful generator:

- heat exchangers to amplify heat transfer between the module and the heat sources,
- an electrical converter to transform the electric power to a voltage level corresponding to the storage device (batteries, capacitors) or to the level corresponding to the needs of the end user.

The efficiency of the overall system can be defined as the ratio of the electrical energy stored or provided to the end user to the energy consumed. The energy consumed is mainly collected at the hot source, but can also include the mechanical energy required to operate the system, such as cooling of the cold heat sink or pressure losses in the heat exchangers.

This efficiency includes the efficiency of the heat exchangers, the efficiency of the TE modules, the efficiency of the electrical convertor and its ability to optimize the electrical load.

The performance of TE modules is low, so the design of generators requires a system approach to optimize the whole system:

- Research into TE materials to achieve the highest possible ZT throughout the generator temperature range.
- Studies on heat exchangers and coupling with TE modules.
- Studies on electrical converters and on the (series, parallel or mixed) electrical connection of modules. These DC/DC converters must be optimized for an electric efficiency close to 1. Boost, Buck-Boost or Cuk convertors are used depending on the output voltage of the TEG (which is mostly related to the number of TE modules in series and on their characteristics) and the desired regulated voltage for the application. They must incorporate a "maximum power point tracking" (MPPT) or "maximum efficiency point tracking" algorithm in order to optimize the point of electrical operation of TEGs and to transfer maximum power to the end user. The most used MPPT algorithms for TEGs are the perturb & observe (P&O) [37–39], the extremum seeking control (ESC) [38,40], the incremental conductance (INC) [41],

the fractional open circuit voltage (OCV) [42,43] and the fractional short circuit current (ISC) [44,45]. This MPPT algorithms can also be combined [46]. These DC/DC convertors and their MPPT algorithms must be carefully selected according to the configuration of the generator and the load requirements.
- Numerical studies to optimize generators. The numerical models must take account of the variations in the properties of the materials according to temperature, the adequate quantity of modules, and the geometry of the modules [47–49].

Unfortunately, these aspects are not independent of each other and overall optimization requires many interactions and powerful computing tools. The economic aspect is also extremely important and must be studied [50].

4. Applications

The conditions in which the TEG is used and the nature of the heat sources are the two parameters used as classification criteria for the presentation of the applications in this chapter. The TEGs have therefore been grouped into five broad categories:

- electricity generation in extreme environments: the heat sources are conventional sources dedicated to TEGs,
- waste heat recovery: the objective is to optimize heat sources that are generally internal combustion engines using fossil fuels,
- decentralized domestic power and combined heat and power generation systems: renewable energies are predominant,
- micro-generation for sensors, microelectronics: power levels are very low and all sources of heat are acceptable,
- solar TEG: the source of energy is the sun.

In the future, it will certainly be necessary to add an application category for organic TEGs.

4.1. Electricity generation in extreme environments

Electricity production in extreme environments must meet a set of very strict specifications. These are usually critical applications that require a highly reliable source of energy over very long periods. Weather conditions can be extreme, either very hot or very cold, very wet or very dry. Maintenance must be as low as possible (in many cases, access to these places is by helicopter only or requires several hours of travel) or non-existent in the case of space expeditions. In space, the generators must be able to operate in a vacuum and withstand high vibrations. Economic considerations are not the most important factor here and rank far behind reliability.

4.1.1. Space exploration

The space industry has used TEGs since the beginning of the conquest of space in combination with thermal generators based on nuclear technology: radioisotope thermoelectric generators (RTGs). Radioisotope generators do not use nuclear fission or fusion, but heat from the natural radioactive decay of plutonium-238 (mainly in the form of 238PuO_2 plutonium dioxide) [51]. The first use of TEG (Pb-Te) dates back to the US Navy's Transit navigation satellite (1961). The satellite was equipped with a SNAP-3 (Space Nuclear Auxiliary Power) nuclear auxiliary generator which generated electric power of about 2.7 W only, but worked for over fifteen years [52]. RTGs were used due to their low mass and extreme reliability. They can operate for several years and even several decades after their launch. They can provide electricity for distant missions where sunlight is insufficient to supply solar panels. Solar radiation is around 1375 W/m^2 on the Earth and falls to 1 W/m^2 around Pluto. The Voyager I and II spacecraft, launched in 1997, also used RTGs, due to their extreme reliability, to power the onboard instruments and transmission systems to the ends of the solar system. The probes are now (October 2015) 19.5 billion and 16 billion km from Earth. Each spacecraft was equipped with 3 RTGs which supplied 423 W in power overall from about 7000 W in heat. This power decreases gradually by about 7 W a year due to the decay of the plutonium and the degradation of the silicon germanium thermocouples. This power is now about 255 W. They have sufficient electrical power to operate until 2020 [53]. The Cassini-Huygens orbital probe launched jointly by NASA and the European Space Agency in 1997 to study Saturn and its satellites, is powered by three RTGs [54].

The main RTGs used in space by American missions can be found on the NASA website [55]. Table 2 presents a summary of

Table 2
Main radioisotope thermoelectric generators and relevant mission.

Radioisotope thermoelectric generator RTG	Electric Power at beginning of mission per RTG	Couple	Number of RTG	Mission	Destination	Year	Design lifetime	Lifetime
Space Nuclear Auxiliary Power SNAP-3	2.7 W	PbTe	1	Transit	Navigation satellite	1961		15 years
SNAP-19B RTG	28.2 W	PbTe-Tags	2	Nimbus III	Meteorological satellite	1969		
SNAP-19 RTG	42.6 W	PbTe-Tags	2	Viking 1	Mars landers	1975	90 days	6 years
			2	Viking 2	Mars landers	1975	90 days	4 years
	40.3 W	PbTe-Tags	4	Pioneer 10	Jupiter, asteroid belt	1972	5 years	30 years
			4	Pioneer 11	Jupiter Saturn	1973	5 years	22 years
SNAP-27 RTG	70 W	PbSnTe		Apollo 12, 14, 15, 16, 17	Lunar Surface	1969–72	2 years	5–8 years
Multi-Hundred Watt (MHW) RTG	158 W	SiGe	3	Voyager 1 & 2	Edge of solar system	1977		Still operating over 38 years
General Purpose Heat Source (GPHS) RTG	292 W	SiGe	2	Galileo	Jupiter	1989		14 years
			3	Cassini	Saturn	1997		Still operating after 18 years
			1	Ulysses	Jupiter	1990		21 years
			1	New Horizons	Pluto(12/2014), Kuiper Belt	2006		Still operating after 9 years
Multi-Mission Radioisotope Thermoelectric Generator MMRTG	110 W	PbTe-Tags	1	Curiosity	Mars Surface Aug 2012	2011		Expected 14 years

the main RTGs and their missions. RTGs can also be considered a combined heat and power system because the heat generated by the radioisotope generators keeps the embedded systems at a reasonable temperature when the outside temperature approaches −200 °C at the confines of the solar system.

The materials used for the thermocouples are PbSnTe, TAGS-PbTe and SiGe. Current research is focusing on improving the performance of proven materials (decreasing lattice conductivity and improving electrical properties) and the study of other materials and couple assembly (Zintl, skutterudite and segmented couples) [56–58].

In conclusion, RTGs are therefore a compact, continuous, highly-reliable source of electrical energy to explore space.

4.1.2. TEG for industrial applications in remote areas

In remote areas, the use of TEGs can produce electricity reliably and with minimal maintenance.

Historically, about a thousand radioisotope TEGs were installed in Russia to power lighthouses and navigation beacons. Very little information is available on these devices, most of which have now been abandoned [59]. Today, the company Gentherm [60] (previously Global Thermoelectric) is the world leader in production of electricity generators for remote areas. The company has existed for 30 years and produced about 22,000 installations. These TEGs use heat produced by the combustion of natural gas, butane or propane. The burner heats one side of the lead-tin-telluride TE modules directly. The other side of the modules equipped with fins is cooled by natural convection. Generators can produce between 15 and 550 W and can be combined for installations of up to 5000 W. These TEGs are used on gas pipelines, wellheads, offshore platforms, telecommunications sites and for security surveillance and monitoring.

For example, according to the datasheet, the 8550 Global Thermoelectric model produces 500 W with daily consumption of 38 kg of propane. Considering an average heating value of around 50 MJ/kg for propane, the energy consumed each day is in the range of 1900 MJ or 528 kW h. The daily production of electricity is 12 kW h. The efficiency of this small plant is around 2.3%. This low efficiency is offset by the benefits of the generators when they are used in desert, well sites, offshore platforms and telecommunications sites in mountains. In these locations, power availability is critical and highly-reliable power with low maintenance is required whatever the climate conditions (hot, cold, wet, dry).

4.2. Waste heat recovery

Reducing greenhouse gas emissions and limiting the ecological footprint are among the major challenges facing humanity in coming years. At the same time, power requirements are increasing every day. A major challenge for researchers and industry is recovery of the lost thermal energy for conversion into electricity. TEGs can contribute to this effort. As an example, the estimation by the Lawrence National Laboratory Livemore [61] of the energy used by the United States in 2014 shows the following significant values (the unit used is the Quad, which is about 293 million MW.h.): production of 12.4 Quads of electricity for residential, commercial and industrial consumes approximately 38.4 Quads of primary energy (mainly fossil fuels or nuclear). 25.8 quads of waste heat are released into the air. The transportation sector consumes 27.1 quads of primary energy and 21.4 quads are released. These results show the margin for progress via waste energy recovery.

The transportation industry is probably the most attractive sector for use of TEGs to recover lost heat. Until now, there have been few solutions to recover waste heat from the exhaust gas of engines. The most active area for energy recovery is the automotive sector where competition towards ever-cleaner cars is very dynamic and encouraged by governments. The aeronautics sector is also looking into the use of hot gases from the engines of airplanes or helicopters. Maritime transport offers interesting prospects due to the presence of a free cold sink (fresh water, sea water).

4.2.1. Automobile

Typically, the energy used in gasoline combustion engines breaks down into 25% for mobility, 30% in coolant, 5% in other parasitic losses and 40% in exhaust gas. For diesel light-duty trucks using 100 kW of fuel power, this represents 30 kW of heat loss in exhaust gases. Converting this lost energy into electricity, even with efficiency of 3%, could represent 900 W of electricity. According to the Fiat Research Centre, 800–1000 Wel means a reduction of 12–14 g/km CO_2.

Looking at the economic context, for example in Europe, the new CO_2 emission performance standard set by the European Commission justifies the research efforts of manufacturers: CO_2 emissions for passenger vehicles stood at 130 g/km in 2012 and are to be drastically reduced to 95 g/km by 2021 (which corresponds to a consumption of about 4 L/100 km). In the case of light-duty trucks, emissions were 175 g/km in 2014 and must drop to 135 g/km by 2020. Car manufacturers will have to pay heavy fines for vehicles exceeding the CO_2 limits of the European Union. From 2012, the penalty is €20 per excess gram and this value will rise to €95 per gram from 2021. The economic incentive has therefore become very significant.

The Fiat Research Centre [62] presented the following performance calculations. Electricity generation by an alternator is as follows: chemical (fuel) energy conversion into mechanical energy has efficiency of around 25–27%, mechanical energy conversion (alternator) into electricity is about 60%. This means that the efficiency of transformation of chemical energy into electrical energy is around 15–16%.

The installation of a TEG on a vehicle must meet the following conditions. The TEG should not change the operating point of the engine; the acceptable pressure losses are very limited (around a few tens of millibars). The maximum temperature of TE materials must be respected and at the same time, in order to have a significant temperature difference, the TEG should be operated near its limits. It is therefore necessary to add control command (sensors and actuators) to bypass part or all the hot gas. The materials must be recycled and environmentally friendly. The economic cost must be competitive. Many manufacturers are working on such subjects.

Gentherm (formerly Amerigon and BSST) is conducting studies on specific geometry modules for BMW and Ford [63]. The Ford group has been conducting research in partnership with the Department of Energy (DOE) of the United States. The research program was based on the installation of a TEG on a Ford Fusion equipped with a 3.0 L V6 engine [64]. The objective was to produce 500 W for a vehicle traveling at about 100 km/h. The results presented by Maranville at the 3rd Thermoelectrics Applications Workshop in March 2012 showed generated power of about 250 W [65]. A bypass was installed on the exhaust system to protect the generator and cooling was by means of liquid and a pump.

The BMW Group has developed various prototypes [66].

In 2003, a prototype using Bi_2Te_3 modules produced 80 W. In 2006, a TEG equipping a BMW535i produced 200 W. In 2008, on the same vehicle, a TEG with PbTe modules produced 300 W. In 2011, a water-cooled prototype mounted on the exhaust of a BMW X6 produced 600 W at a speed of about 125 km/h. The fuel gain was around 1.2%. Studies have also been carried out to implement a TEG on the exhaust gas recirculation system (EGR). The exhaust gas recirculation system recirculated a portion of the exhaust gas back to the engine cylinders. This device allows a reduction in nitrogen oxide production, but the exhaust gas must be cooled. The device therefore already contains a heat exchanger and a control valve. It is possible to add thermoelectric modules at lower cost [67].

General Motors installed a TEG on a Chevrolet Suburban [68,69]. This vehicle is comparable to a European light-duty truck, whose operating point is not too penalized by the overload due to the TEG. The first two versions of the prototype used Bi_2Te_3 modules. The device installed in the exhaust also included a bypass in order to keep the temperature of the generator under 250 °C. The experiments first showed a significant temperature drop at the interface between the gas and the heat exchanger, and then that the temperature decreased along the hot heat exchanger. At the input of the TEG, the exhaust gas was about 400 °C and the temperature of the heat exchanger (which is approximately that of the hot side of the TE modules) was only 250 °C. Moreover, this temperature of 250 °C at the inlet of the heat exchanger dropped to 148 °C at the output of the exchanger, which is rather low. Measurement of the open circuit voltages also showed that the effective temperature difference between the two sides of the TE materials was only 50 °C, far less than the temperature difference between the exchanger and the coolant. The first results with Bi_2Te_3 modules were disappointing: about 25 W when the exhaust gas is around 400 °C. The problem was identified and was mostly due to contact resistances. A new prototype using skutterudite-based modules which accept higher temperatures was studied. A first experiment with a reduced number of modules allowed General Motors engineers to estimate that for a temperature difference of about 500 °C at the inlet, a power of 230 W could be obtained with a complete generator.

In Europe, Renault Trucks, Volvo, supplier Valeo and academic laboratories worked on the RENOTER "energy recovery from the exhaust of an engine thermoelectricity" project from 2008 to 2011 [70,71]. The vehicles in question were cars with a 2.0 L diesel engine with a TEG (target 300 W power) installed in the exhaust, and large trucks with 11 L engines with a TEG (target 1 kW power) installed in the exhaust gas recirculation system. Significant work was done on the design of the heat exchanger in order to optimize the interface between the TE materials and exhaust gas. This exchanger causes a small pressure drop (less than 30 mbar). Non-toxic TE materials were developed by the partner laboratories: MnSI and Mg_2Si to meet goals of moderate cost and compatibility with the resource volumes required for the automotive market. The RENOTER project concluded that a TEG with Mg_2Si-MnSi materials can generate up to 130 W for a passenger car diesel exhaust in highway conditions, which remains low. However, power may rise to 250 W for gasoline passenger car exhaust and 350 W for a truck exhaust gas recirculation cooler by improving parasitic electrical resistance (contact and connections) and by improving the performance of the p-doped material. This program is being continued with the RENOTER 2 Project which started in 2013. This new program targets hybrid gasoline vehicles and industrial vehicle exhaust gas recirculation systems. Valeo plans to produce magnesium silicide TEGs for 10,000 vehicles in 2018.

More recently, FIAT and Chrysler presented a light commercial vehicle equipped with a TEG [72–74]. The project financed by the European Union was called HEATRECAR (Reduced energy consumption by massive thermoelectric waste heat recovery in light-duty trucks). Work has been done on the heat exchanger and on the size of the TE modules which have been reduced (16×16 mm^2) in order to decrease contact resistance. The performances achieved by the TEG are encouraging: a 3.9% fuel economy improvement (6.7 g CO_2/km reduction) over the worldwide harmonized light vehicles test procedure (abbreviated WLTP) cycle. This TEG used Bi_2Te_3 modules with limited operating temperatures. High-temperature material should be used in future applications to take full advantage of TEG power generation. A cost analysis of the prototype gives a current specific cost per watt of electricity produced of around €8.4/W. The cost breakdown analysis shows that 20% of the cost is due to material cost (Bi_2Te_3) and up to 73% of cost is due to TE module manufacturing. The maximum cost accepted by the automaker in terms of €/W has been estimated as follows:

- private conventional car or gasoline hybrid taxi: €0.5/W,
- light-duty truck or freightliner in USA: €0.7/W,
- diesel light-duty truck or freightliner: €1.5/W,
- conventional diesel taxi: €3/W.

Scania and TitanX exhibited a heavy-duty truck at the 34th Annual International Conference on Thermoelectrics (ICT2015) with an engine equipped with an exhaust gas recirculation system [75]. Two TEGs were present on the truck: one in the exhaust gas recirculation system path and one in the exhaust gas path located after the treatment system (ATS). The target for the sum of both TEGs using today's commercially-available modules was 1 kW. The measurement showed that for low engine load, most of the electric power was produced by the TEG located after the treatment system but that for heavy engine load, the TEG located on the recirculation system, produced almost the same power. This study showed the interest of combining the two systems. The measured electric power reached 775 W for an engine speed of 1300 rpm and 100% load.

These different studies have demonstrated the technical feasibility of TEGs for the automobile industry, but the cost of a Bi_2Te_3-based TEGs is still too expensive. The roadmap for the future is to develop TEGs with low-cost materials and with low-cost automated process production.

4.2.2. Aircraft and helicopters

A significant amount of heat is released from aircraft jet engines and turbine engines for helicopters. A preliminary study conducted by Boeing Research & Technology showed that a fuel reduction of 0.5% or more is achievable with TEG. For U.S. commercial planes, a 0.5% fuel reduction means a $12 M monthly operating cost reduction.

Several patents have been filed [76–78]. However, a study [79] on turbine nozzles with Bi_2Te_3 modules shows that the electric power produced in real operating conditions is significant but currently insufficient if the weight of the cold exchanger is included. On the turboshaft, heat can be collected on the compressor segment, on the burning chamber and on the exhaust pipe. TEGs could be added to these different places but must have no influence on the working point of the turboshaft, which rules out use of performing heat exchangers. Furthermore, heat going through the TEG must be released somewhere. Fuel, oil, air or compressed air are available, but need to be brought to the TEG, which increases the overall weight of the system. The integration of TEGs (0.05 kW/kg-module as state of the art) do not fulfil the power density requirement (0.5 kW/kg) for aircraft. Thereafter, the Thetagen [80] European study confirmed these results. The roadmap for the future is probably to add the constraints of the TEG to the design of the aircraft engine or to add them in an area where there is already a hot heat flow and a cold heat flow. The new light TE materials will also contribute, but it must be remembered that the weight of the heat exchanger is also to be included in the total weight.

4.2.3. Ships

Until now, relatively few studies have been carried out on ships because of the absence of very strict international regulations. Shipping is a large and growing source of the greenhouse gas emissions that are causing climate change. The European Union wants to reduce emissions from international shipping. The European Commission has proposed that owners of large ships using EU ports should report their verified emissions from 2018. This sector should grow rapidly due to the arrival of new, more stringent rules [81]. Kristiansen [82,83] has studied the opportunity of TEGs for large ships. On large vessels like oil tankers, container ships, cruise ships or ocean liners, the main engine (8–80 MW) is the main heat source on board. Traditionally, the heat released by the engine is already used to heat heavy fuel oil and accommodation areas, and to generate fresh water. These uses decrease the temperatures of waste heat to a level which is too low for optimal use of TEG. On these ships, there are also auxiliary engines but they work intermittently when arriving or leaving harbor and are not working enough to produce a significant amount of energy. On these ships, there are also large incinerators to burn the sludge produced by the heavy fuel oil. The incinerator capacity in kW represents around 3% of the main engine power. These incinerators work intermittently but are used between 12 h and 20 h per day. The heat released by the incinerators is not very attractive as a heat source for the ship, mainly because of the limited running time. Introducing a boiler to produce electricity calls for additional safety measures, extra installation and daily maintenance. Incinerators are therefore a good candidate for TEGs. They have a high possible temperature difference and the advantages of the TEG comply with design criteria like reliability and low maintenance.

For smaller ships, TEGs are also an opportunity because weight is not a problem, the cold source (water) is free and maintenance must be as low as possible [81,84,85].

4.2.4. Locomotive industries

Bombardier [86] has filed a patent describing a TEG with a latent heat accumulator thermally connected to the high-temperature side of the TEG. This heat accumulator can smooth out the high temperature fluctuations which are encountered in a diesel-electric locomotive for example.

4.2.5. Recovery of waste heat in industries

Industry is a field where heat is often a byproduct of the process. In many cases, part of this heat is reused for heating networks or converted into electrical energy by means of steam turbines, Rankine or Stirling engines, although most of the time this heat is released into the atmosphere. Various waste heat recovery projects using TEGs were studied.

In 2009, KELK Ltd. started a field test of a thermoelectric generation system [87] at a carburizing furnace of Komatsu Ltd., Awazu Plant. Residual carburizing gas containing CO, H_2 and N_2 was burned in the plant. This resulted in a 20 kW burning power which constantly heated up the hot side of a TEG. The TEG was made of 16 Bi_2Te_3 modules and a heat exchanger which collected approximately 20% of the heat (4 kW). The maximum electrical output power was around 214 W, which represents an efficiency of 5%, but the power used to cool the cold side of the modules was not included in these results.

Aranguren et al. [88,89] have conducted experimental investigations and mathematical studies of a TEG dedicated to recover waste heat from a combustion chamber. In their investigation, they included the energy used by the cooling system of the TEG and discussed various cold heat exchangers. They have concluded that their prototype has potential production of 100 W/m^2. This result was extended to a large industrial chimney on a ceramic tile furnace which has a flue gas mass flow of 18,400 Nm^3/h and a temperature of 187 °C. Predicted annual electric production was estimated to be 136 MW h per year.

The steelmaking industry produces a lot of waste heat, especially radiant heat from steel products. TEGs are good candidates to recover the radiant heat from molten metal. JFE Steel Corporation (JFE) in Japan has implemented a 10 kW TEG system (about 4 m × 2 m) using radiant heat from the continuous casting slabs [90–92]. This TEG is connected to the grid. It consists of 896 TE modules (56 TEG units of 16 Bi_2Te_3 TE) and outputs about 9 kW when the slab temperature is about 915 °C.

Cement production is also an energy-intensive industrial process. Luo et al. [93] have studied the possibility of adding TEGs to Portland cement manufacturing. They estimated that approximately 10–15% of the energy is dissipated directly into the atmosphere through the external surface of the rotary kiln. This kind of wasted heat is difficult to recover because of the permanent movement of the kiln. For a kiln of 4.80 m in outer diameter and 72 m in length, the total heat loss without the TEG recovery system is approximately 10,000 kW. They imagined a coaxial shell around the rotary kiln covered with Bi_2Te_3–PbTe hybrid TE modules on the inside. They elaborated a mathematical model that predicted that for 20 units with 3480 TE modules ($30 \times 30\ mm^2$) each, the overall TE system can produce 210 kW and save 3280 kW due to the insulation shell. The contribution of thermoelectric generation is approximately 2%.

These different examples or industrial studies show that TEGs have two main prospects in industrial manufacture: either in cases where it is difficult to recover the waste heat by conventional systems (radiated heat energy), or in the event that new materials can produce maintenance-free and low-cost electric power, despite low efficiency.

4.3. Decentralized domestic power and combined heat and power (CHP) generation systems

Electricity is mainly produced by centralized power stations and distributed by grids. However, many places are not yet electrified. In developing countries, the combination of low power requirements and low population income in isolated villages prohibits connection to the electric grid. In developed countries, connection to the grid is not the most interesting solution in some cases and greener alternative solutions are being studied. For different reasons, autonomous power production concerns both developing and developed countries. TEGs are sometimes used only for electricity production, but most of the current projects concern TEGs used in combined heat and power systems. One of the earliest domestic applications, a stove-top generator, was proposed by Killander [94] for the rural far north of Sweden. Killander noticed that "an unverified side benefit of the generator is that it may have decreased the amount of fuel burn". They realized that the fan cooling the TEG cold side circulated the air in the room and thus increased comfort. The system was a simplified CHP system.

4.3.1. Domestic TEG in developing countries

In developing countries, an estimated 1.2 billion people – 17% of the global population – do not have access to the electricity grid [95] and yet still have electrical needs. Biomass is the main energy source. In these rural areas, wood is burned with very low thermal efficiency – less than 10% for three-stone fire places and only around 35–40% for rocket stoves and top lid updraft stoves. It contributes to local deforestation, increases labor for women and children and is a cause of insecurity as people collect firewood from ever further away in politically unstable countries. The fumes are also highly toxic [96]. According to the International Health Organization, the use of wood and waste for cooking and heating causes 400,000 premature deaths a year in India, mostly women and children. For example, in India the amount of particles exceeds 2000 μg per cubic meter in a house where biomass is used for cooking, far greater than the standard in the USA which is 150 μg per cubic meter [96–98]. Installation of efficient wood stoves is critical to health and safety. These efficient stoves require the use of fume extractors to improve combustion. Electricity is therefore necessary both for the stoves and for the basic needs of the inhabitants.

Grid connection of villages and homes without electricity has a significant cost with two main components: the price of the installation of new power lines and the cost of electrical distribution over long distances. In 2005, the International Bank for Reconstruction and Development studied the cost of installing new lines in the state of Bahia in Brazil [99]. The cost of connecting a village which is less than one kilometer from the network was estimated based on the number of electric poles required per capita. For one pole per household, the cost was $300. When the village is more dispersed and requires more than two poles per household, the cost increases to $1000. It soars to $4000 when more than 4 poles per household are needed. This amount increases with distance and depends also on the nature of the terrain. The delivered cost of electricity was studied in India by Nouni [100]. It varies between $0.07 and $5.1 per kW h depending on the requested peak power and average consumption. The worst case is for a remote village located at a distance of 20 km from the power line, demanding peak power of 5 kW and with a load factor of 0.1 (ratio of average power to peak power). This corresponds to a village where electricity is mainly used for a few hours at night for lighting (villages with few houses in mountainous areas without commercial or industrial activity). These economic results clearly show that grid connection is not a solution for these very low-income populations.

Power production through decentralized autonomous systems is the only financially achievable solution. Solar energy immediately springs to mind, but it requires large storage capacities for periods without sunshine (night, fog and monsoon).

TEGs are a solution to provide a few watts for lighting or for charging mobile phones and powering electric extractors. The low efficiency of the TE modules is not a problem when the contribution of the TEG allows an improvement of combustion efficiency. For 3 h of combustion, a family uses around 5–10 kg of wood, which means energy of around 17–34 kW h. Improving this combustion is a far greater contributor to reducing global energy consumption than the 5–30 W which are produced by the TEG. In this case, the main specifications for the design of the TEG are to provide enough electricity to power the extractor - possibly to charge a phone and give some light – and to be robust because maintenance is very awkward in isolated areas.

A few laboratories have conducted research into installation of TE modules (Bi_2Te_3) on cookers or stoves. In the first step, these first prototypes aim mainly to produce electricity. Nuwayhid et al. [101] have studied the possibility of using a proportion of the heat from 20–50 kW wood stoves to provide a continuous 10–100 W electric power supply. In a first prototype, they used cheap Peltier modules for their TE generator. The maximum power for a module was very low (1 W) mostly because of the limited temperature difference due to the maximum temperature supported by the module and also because of the geometry of these modules which are optimized for cooling and not for generating power. They already noticed the limitation of using Bi_2Te_3 for this application. In a later prototype [102], their TE generator used 1, 2 or 3 commercially-available, low-cost power generator modules. The cold side of the TE modules was cooled naturally with the surrounding air. They got maximum power of 4.2 W for one TE module and showed that the output power per module decreased when the number of TE modules in the TE generator increased. This is a result of the reduction of the temperature difference between the hot and cold surfaces. Increasing the number of modules does not always increase power, as shown in Favarel [28]. They also tried to improve heat transfer, making a TE generator using heat pipes for the heat sink [103]. The maximum power was about 3.4 W. Lertsatitthanakorn [104] investigated the same type of prototype and obtained a power output of 2.4 W. He added an economic analysis indicating that the payback period tends to be very short. Masbergen et al. [105,106] studied a TEG using smoke as the hot source and the outside air in forced convection as the cold source. The electrical power obtained was of the order of 4 W after the DC/DC controller. Rogers and Henderson [107] have developed a portable lighting “Twig Light” for Ghana, using a few twigs to provide half an hour of lighting. Rinalde et al. [108,109] studied a TEG using smoke as a heat source and water circulation for the cold source. The power obtained in the laboratory with a $B_{i2}Te_3$ module was of the order of 10 W but pump consumption was not specified and the electricity storage device was not yet operational. More recently, Shaughnessy et al. [110] have developed a TEG adapted to portable biomass cooking stoves currently used in Malawi. Heat is collected from the fire and delivered to the hot side of the TEG through three copper rods which protrude into the centre of the stove. The cold side is cooled by a fan powered by the TEG. The aim of this TEG is only to produce electricity for rural populations. Five technology-demonstrator, electricity-generating stoves have been integrated with locally-produced clay cooking stoves in Malawi. A 80-day field trial [111] was carried out. The data collected over the 80-day field trial indicates that the generators performed adequately and enabled the user to charge LED lights and mobile phones. These results show that the technology can support the energy access issue, which is around 3 W.h daily for the population in question. The authors pointed out that the air cooling system could be directed into the stove in order to improve combustion. The TEG design has been refined based on the results of the field trials [112,113]. The new generator design was less expensive, mechanically more robust and easier to assemble than the initial design. A second field trial was carried out in which some of the TEG-stoves experienced greater cold side TEG temperatures than expected. This was identified by the authors as being due to extensive use of the battery by the inhabitants. When the battery voltage becomes too low, the fan does not cool the cold side of the TEG. This trial shows the difference between laboratory tests and field uses, and the importance of adding electronic protection to the DC/DC converter.

The second and third steps for researchers were to produce electricity in order to increase combustion performance by adding fans or smoke extractors and using TEGs in CHP systems. We have been working on such a project in our laboratory since 2009. The aim is to power a fan drawing air into the combustion chamber of a stove in order to increase the air/fuel ratio to achieve complete combustion. The first studies showed the interest of installing the TEG between the hot gas and the tank used to produce hot water [114–116]. A stove installed in our laboratory [117] has been equipped with a TEG located in the flue and acting as a heat exchanger between the flue and the hot water tank. This generator consists of two series of modules. The first series in the flue consists of an exchanger with 4 TE modules connected electrically in series to a DC/DC converter. The second series located after the first one in the flue has a lower average temperature. It consists only of three TE modules in series in order to optimize production. These three modules are connected to a second DC/DC converter. The two DC/DC converters include a maximum power point tracker (MPPT) [39]. These converters charge a battery and power the smoke extractor. Tests showed the autonomy of the stove and the possibility of having a few extra watts to charge a phone or for lighting.

Najjar [118] presented a multipurpose stove with a 12-module TEG used as a heat exchanger between the hot combustion gas and the room air (combined heat power system). The temperature difference was quite low (less than 45 K) and the peak electrical power less than 17 W for 12 modules, but the TEG improved the exchange with the air. More than 80% of the energy produced in the combustor is transformed through TEG fins to space heating.

Lettsarkinon [119] studied the possibility of self-powering a rice husk gasifier in order to use it as a cooking stove. Electrical energy is needed to drive a blower for the gasification process. The first experiment showed the need to improve the system as the power produced by the prototype was not sufficient to power the fan. Risha Mal [120,121] presented a prototype of a rudimentary cooking stove including a TEG. The power produced is mainly used by a fan in order to improve combustion. Biolite [122] has also marketed a home stove which drastically reduces particulate matter and carbon emissions.

A review of the development of stove-powered TEGs can also be found in [123].

In conclusion, different systems are currently being studied and one device marketed: TEGs are a solution for providing small amounts of electricity (mobile phone charging and LED lighting) in developing countries. They will also allow the distribution of more efficient stoves which need the addition of an extractor or a fan in order to improve combustion. Thermoelectric performance is not an obstacle when set against the improvement to combustion efficiency which can range from 10% to 80% for multifunctional stoves. The main technological challenge relates to the complexity of combustion cycles for which maximum temperatures can vary greatly depending on the wood used and the habits of the users of the stoves. These systems use Bi_2Te_3 modules and are undersized to withstand large variations in temperature during wood combustion. The difficulty in disseminating this technology is certainly also related to the cost of TEGs. The arrival of new TE modules with extended temperature ranges and lower costs should accelerate the development of these devices.

4.3.2. Domestic TEG in developed countries

TEGs are not limited to the domestic sector in developing countries. In developed countries, the quantity of high-performance wood stoves is increasing very quickly for economic and environmental reasons. These sophisticated stoves need intelligence to control the combustion in order to meet minimum emission requirements. Electric components (sensors, fans, valves, actuators and microcontrollers) are necessary for these operations. Availability of electricity is essential. In the case of isolated houses used at certain times of the year, such as second homes, the grid connection can be very expensive for occasional occupants. At the same time, the demand for comfort is there. Renewable energy from the sun is sometimes the answer but has the disadvantage of being unavailable during poor weather conditions and at night, and requiring huge batteries to store the energy whereas the heat of the stove can be used to generate electricity. Even in homes connected to the grid in some European countries, power cuts occur more often during cold spells and people are particularly unhappy to be increasingly deprived of heating. A system guaranteeing the autonomy of the stove is a great value.

These niches have been explored by Austrian company “Bioenergy 2020+” which develops wood-pellet CHP combustion units [124–126]. The TE modules are arranged around the combustion chamber with an exchanger which is dimensioned to avoid exceeding the TE material operating range (Bi_2Te_3). The cold source is either the outside air in the case of stoves used only for heating, or hot water in the case of boilers. Various prototypes have been produced: the TEG 250 equipped a 10 kW boiler and produced 170 We, the TEG400 cooled by ambient air equipped an 8 kW stove and provided 100We, and the water-cooled TEG400 was installed on a 12 kW boiler and provided 300We. Despite these interesting results, market production has not started, probably due to some defects in the Bi_2Te_3 modules.

Montecucco et al. [127] have studied a CHP system for solid-fuel stoves with a TEG using forced water cooling. The TEG heat exchanger system was added to the top of the stove. A pump circulates water from a 60L water tank to the heat exchanger of the TEG cold side. A complete TEG system including an MPPT DC/DC convertor charging a battery was experimented. Under laboratory conditions, this device produced almost 600Wth and 27Wel on average during a 2-h burning experiment. Although interesting, these results will probably not be so good in real conditions because of the necessity of undersizing the TEG in order to protect the Bi_2Te_3 modules from overheating. Despite the great interest of this solution, this device adding a pump is probably a little bit too sophisticated for developing countries and is therefore presented in the developed countries section.

Alanne et al. [128] have conceptualized a cogeneration system in which TE material is integrated directly into the heat transfer surfaces of the combustion chamber and convection tubes of a conventional domestic wood-pellet-fired boiler. The aim was to find the highest possible conversion efficiency with the slightest structural change in a commercial boiler. The results of computational analysis should be taken with care because the model uses the properties of Bi_2Te_3 at temperatures not supported by this material. However, this study shows the possibilities which can be offered by the new materials with extended temperature ranges.

TEGs could also be developed in order to improve the efficiency of old stoves: Ecofan [129] sell heat-powered fans for stove heaters. The airflow created by the fan distributes the warm air from the stove more evenly in the room. According to Ecofan [130], the use of an Ecofan 800 fan during woodstove operation provides an average fuel saving of 14% for a range of standard test conditions studied while maintaining user comfort levels over extended periods.

Adding TEG to gas heaters has been explored by Codecasa. The first TEG was tested on an autonomous heat-radiating gas heater for commercial outdoor environments [131,132] and a power of 8 W was obtained. Another prototype has been developed for gas combustion heat radiating units used in residential and industrial environments [133]. These heaters operate autonomously with a local gas feed. Use of a fan convector to force air through the heat exchanger can increase comfort, reduce temperature stratification, and improve heating efficiency. The TEG can permit local production of electric power to support the fan without the need for any connection to the electricity grid.

Zheng [6,134] presented a complex domestic system combining a gas boiler and a solar concentrator with two TEG blocks. The domestic hot water is preheated on the cold side of the TEG units. The heat is provided either by the hot gas of the boiler or by the hot oil of the TEG. The authors have mainly conducted experiments on oil-powered TEGs.

4.4. Micro-generation for sensors, microelectronics

To be competitive, industry requires sensors in its products and in its factories. By incorporating new sensors in factories, manufacturers can improve product quality and reduce downtime. Current intelligent sensors require only a few hundred microwatts or a few milliwatts to operate. Powering these devices from the electrical grid often requires very long cables to provide very little energy, while requiring forward planning of the layout of these cables. The power source should match the lifespan of the sensor. Most wireless sensors are designed to last 15 years or even more, but batteries limit this autonomy to a few years and battery changes in industrial applications are often difficult and costly due to geographical constraints of access restrictions in chemical facilities, power plants (including nuclear), military facilities or secure data centers. Manufacturers are therefore looking for micro generators producing a few milliwatts to power these micro-instruments and make them autonomous. In factories, heat sources are numerous: hot fluid pipes, ovens, steam lines, motors, air conditioning, heating, ball bearing etc. TEGs are an ideal candidate for this challenge. Low maintenance and good performance in difficult environments are also important advantages for TEGs. Very small TEGs (a few square millimeters) are a solution to power these sensors permanently.

Micropelt [135] and Laird [136] are developing such devices. For example, Micropelt MPG-D751 modules with sizes of $3.3 \times 4.2 \times 1.1\ \text{mm}^3$ can produce more than 1 mW for a temperature difference of 10 °C and more than 10 mW for a difference of 30 °C. Open circuit voltage is 1 V for a temperature difference of 10 °C and 3.7 V for a difference of 30 °C. The high number of couples, 540 deposited on the silicon substrate, allows for high voltage levels and facilitates DC/DC conversion. These modules are then integrated into various devices including hot and cold exchangers, a DC/DC converter and a storage capacitor or a small battery. Autonomous sensors and actuators are already available: the Micropelt mNODE monitors temperature continuously, and the Micropelt iTRV is a self-powered thermostatic radiator valve which communicates with thermostats via standard radio protocols enabling room temperature management. The Laird WPG-1 is a self-contained thin-film TEG that harvests waste heat to power wireless sensors. Perpetua [137] has developed a small energy harvester, Power Puck, which is compatible with wireless sensors and transmitters for leading providers of wireless industrial instrumentation: Emerson Rosemount [138], GE Measurement & Control [139] and Honeywell Wireless. This TEG has a magnetic base and can easily be installed on any flat metallic heat source. Power Puck allows a significant extension of battery life using energy from temperature differences, and allows an increase in data collection intervals without an impact on battery life. ABB [140] also sells a thermoelectric-powered temperature sensor. Wang et al. [141] studied a microTEG wireless sensor network for building energy management including temperature, humidity and light sensors.

Samson et al. [142–144], followed by Elefsiniotis et al. [145–147], have explored thermoelectric energy harvesting using phase change materials (PCMs) for low-power wireless sensor systems in aircrafts. The introduction of phase change materials as a heat storage unit allows exploitation of temperature changes over time and can improve these small generators. In the first prototype, the phase change material (ice water mixture) which is at the ambient temperature inside the fuselage before the takeoff, serves as a hot spring after takeoff. The fuselage, whose temperature decreases after takeoff, serves as a heat sink. When taking off, the fuselage temperature decreases quickly while the ice water mixture takes approximately 40 min to reach the fuselage temperature. The TEG produces enough electricity to power a microwave sensor group transmitting information on the fuselage structure. This microTEG uses modules from Micropelt. The potential of these TEGs has been proven over a six-month flight test campaign. More recently, Elefsiniotis et al. [148,149] have extended this idea to other PCM in order to use this principle in high temperature environments (aft pylon engine fairing area) in the aircraft. Shi et al. [150] studied self-powered wireless temperature sensors using paraffin (PCM) for the cold side that can detect fire before it develops to flashover state.

For extreme conditions, Xie et al. [151] have developed a TEG that harvests seafloor hydrothermal energy through a heat pipe and converts heat to electrical energy. The TEG continuously produced 2.6–3.9 W electric power during the field test, and this power was used to power a data logger and an LED lamp. This TEG can be an alternative renewable power source for deep sea observation where cable instrumentation is not practical.

Using the human body as a heat source for TEGs has also been the subject of several studies [152–159]. The main problem is the thermal contacts between TEG-human skin and TEG-air which allows only a small temperature difference and limits the application to very low-power applications.

Wireless applications are growing increasingly and the electrical consumption of sensors, actuators and microcontrollers is constantly diminishing, so micro-TEGs should develop further. The technology is maturing. Bi_2Te_3 is particularly suitable for the temperature ranges encountered and small amounts of materials are not an obstacle to development. The spread of these devices will be mainly linked to their promotion. New materials may open niches in extreme environments. Conformable Organic TE materials (for the human body for example) could also extend this scope.

4.5. Solar thermoelectric generator (STEG)

The basic idea is to use the sun's heat as a heat source for the TEG. A simplified calculation neglecting Joule and Seebeck effects allows the magnitude of heat flux density in a TE pellet to be determined.

Assuming that correct performance of a TEG is obtained when the temperature difference ΔT across a thermocouple is in the order of 100 K and the length L of a thermocouple pellet is in the order of one millimeter and the thermal conductivity k of the TE materials is of the order of $1\ \text{W m}^{-1}\ \text{K}^{-1}$, then the magnitude of the heat flux density ϕ through a TE pellet is in the range of 105 W per square meter as given by the formula.

$$\phi = k\frac{\Delta T}{L} = 1\,\frac{100}{0.001} = 10^5\ \text{W/m}^2$$

However, solar intensity on earth is of the order of $10^3\ \text{W/m}^2$. It is therefore imperative to amplify this intensity by a factor of 100. Different options can be used:

- directly concentrate the solar flux received either by designing special TE couples with thermal and optical concentrators or by using classical solar concentrators,
- use of the TEG as a heat exchanger in a CHP system.

The waste heat on the cold side of the photovoltaic (PV) panels or the solar heat stored in pound can also be a way to produce electricity with TEG.

4.5.1. Special TE couples

The Massachusetts Institute of Technology [160,161] has demonstrated a flat-panel solar thermal to electric power conversion technology. The concentrating STEG comprises an optical concentration system and thermal concentration absorber. A glass enclosure envelops the absorber and the TEG in order to maintain a vacuum to reduce thermal losses. The developed STEGs achieved peak efficiency of 4.6% under $1\ \text{kW m}^{-2}$ solar conditions. The difficulty for this kind of generator is concentrating the heat on the thermoelectric elements and finding materials that can withstand very high temperatures (>1000 °C). Kraemer et al. [162] also proposed to integrate STEGs in solar hot water vacuum tube systems for cogeneration application, which shows potential to provide cost-competitive domestic hot water and electricity. Baranowski et al. [163] showed that, with current TE materials, a total efficiency of 14.1% is possible with a hot side temperature of 1000 °C and a concentration of solar intensity by 100, including a non-ideal optical system. Olsen et al. planned to test a new STEG in a high-flux solar furnace in order to reach 15% efficiency. Chen et al. [164] and Kossyvakis et al. [165] also conducted calculations to optimize STEG design.

4.5.2. Classical solar concentrators

Lertsatitthanakorn et al. [166] studied a double-pass TE solar air collector with flat plate reflectors. The flat plate reflectors were used to concentrate solar radiation onto the TE solar air collector. The optimum position of the reflectors was studied. 2.1 W was produced. A second study [167] used a parabolic dish concentrator to collect heat on a commercial TE module. 1.4 W was obtained. Ozdemir et al. [168] tested a prototype of solar heating TEG cooled by a chimney. 0.8 W was obtained.

4.5.3. CHP solar systems

Wei He [169,170] explored the coupling of solar water heating with a TEG. The experimental prototype unit was based on a solar concentrator with glass evacuated tubes. The heat-pipe transfers the solar heat absorbed within the glass evacuated tube to a water channel. The TEG works as a heat exchanger between the heat pipe and the water channel. Electrical efficiency is low, at around 1 to 2%, but as it is a CHP system, the overall efficiency must be taken in account. The efficiency of the hot water production is quite good (about 55%). Compared to organic rankine systems, the device has the advantage of having no moving parts. Chavez Urbiola et al. [171,172] presented a solar hybrid electric/thermal system with a radiation concentrator. The concentrator illuminates a TEG which is cooled by a thermosiphon providing hot water. The system generates 20 W of electrical energy and 200 W of thermal energy stored in water with a temperature of around 50 °C.

4.5.4. Other systems

Another idea was to add TEGs on the rear side of photovoltaic panels to collect lost heat. The performance of this combined solar photovoltaic and TEG system has been examined by Bjork et al. [173] using an analytical model for four different types of commercial photovoltaic panelss and a commercial Bi_2Te_3 TEG. The degradation of photovoltaic performance with temperature due to the TEG was shown to be much faster than the increase in power produced by the TEG, due to the low efficiency of the TEG. Recently, Attivissimo et al. [174] carried out the same study and found more promising results, while Makki et al. [175] investigated a more complete system with a heat pipe removing the heat on the cold side of the photovoltaic -TEG system. Calculations showed an increase of 1–2% in efficiency compared to a conventional photovoltaic panel.

Singh [176] experimented the use of salinity gradient solar ponds which are capable of storing heat at temperatures of up to 90 °C. The temperature difference between the upper convective zone and lower convective zone of a salinity gradient solar pond can be in the range of 40–60 °C. The designed experimental rig was able to provide a maximum power of 34 W.

5. Conclusion

In this review of thermoelectric applications, new thermoelectric modules with improved ZT, larger operating range allowing their uses with higher temperature differences and made with low-cost materials that counteract the negative effect of low efficiency of thermoelectric generators, have been presented. Starting points to system design have been described.

For years, the development of TEGs has been limited to Space and hard access areas where reliability is critical. These extreme environment applications have very high added value but they are niche applications for which the market is very limited. In these applications, TEGs have proven their extreme reliability. Studies conducted by the space research agencies resulted in the discovery and development of most of the TE materials. These materials are or will be used in the industry today and in the future. However, it is very important to note that in these cases, the heat sources do not vary significantly and the materials are therefore not subject to high thermal stress. It is quite different for others applications presented in this review where the temperatures of heat sources are changing and where the materials often experience very severe temperature cycles.

Waste heat is a big challenge in transportation and industry. TEGs are competitors which, despite their low efficiency, can contribute to gaining a few percent in overall efficiency and to reducing the environmental footprint. Their main advantages are their compactness and low maintenance. Different studies have demonstrated the technical feasibility of TEGs for the automobile industry, but the cost of a Bi2Te3-based TEGs is still too expensive. New materials characterized by low costs and larger working ranges should allow the imminent arrival of TEG on vehicles. These new materials also offer very interesting perspectives for the maritime sector and boost research in the aircraft industry. The roadmap for the future is to develop TEGs with low-cost materials and with low-cost automated process production.

In developing and developed countries alike, the various studies and examples presented in the review, show that TEGs are a good solution to provide some electricity when grid connection is not possible. This ability to produce some electricity also improves the efficiency of heat generating devices slightly or consistently. The poor performance of TE materials is then masked by the improvement in the overall system. Well-designed systems can overcome the issue of low efficiency and bring significant economic or environmental added value. The recent availability of new cheap materials and the starting of assembly of TE modules by manufacturers will permit mass-market development in combined heat and power systems. The large-scale distribution of these systems will be effective once TE modules with similar properties to those of Bi2Te3 will be available at low cost.

The increasing needs of self-powered micro-sensors in industry will drive the development of micro-TEG. The sun as a free heat source has also boosted research on solar thermoelectric generators. Solar thermoelectric generators are not yet mature. Future research is needed. But the availability of high-temperature TE materials combined with the design of high-tech TE couples integrating optical and thermal concentrators can be an issue in developing competitive products that are comparable to photovoltaic. The use of TE modules in hybrid CHP solar systems can also increase the efficiency of overall systems by a few percent. Current research into organic TEGs is promising and new applications in clothes or human objects can easily be imagined.

The potential of the numerous applications described in this paper clearly demonstrates that, almost anywhere in industry or in domestic uses, it is interesting to check whether a TEG can be added whenever heat is moving from a hot source to a cold source.

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