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## Article

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# Analysis of the use of Renewable Energies in Colombia and the Potential Application of Thermoelectric Devices for Energy Recovery

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## ABSTRACT

This study investigates the current situation of electricity generation from non-conventional renewable energy sources (NCRES) in Colombia. In general, it was shown that Colombia has potential in renewable sources such as solar, wind, and biomass. However, barriers such as lack of human capital, policies focused on conventional technologies and high investment costs have impeded their growth. Although the development of these sources has been encouraged through Law 1715 of 2014, more policies and developments are needed to promote this type of NCRES. The use of thermoelectric devices (TED) can become a potential NCRES alternative, while the political and technological conditions improve in Colombia. Around the world, TEDs have allowed the recovery of waste heat in a variety of industrial applications and the automotive sector. They are allowing in the latter, not only the generation of electric power, but also the reduction in engine emissions. Besides, its characteristics have allowed it to be used for the generation of electric power, both in developed and developing countries. In this document, an example presentation is developed that demonstrates the applications of the TED in the cases above to demonstrate the potential that the TED can have in almost any place that has a heat source.

**Keywords:** Electricity Generation, Energy Policy, Energy Recovery, Non-conventional Renewable Energy, Thermoelectric Device

**JEL Classifications:** L78, L90, O31, Q20

## 1. INTRODUCTION

The environmental problems caused by global warming and the progressive depletion of fossil fuels have generated worldwide interest in investigating new renewable energy sources (RES) to guarantee energy security (Camargo et al., 2018; Gielen et al., 2019). The use of RES has increased in industrialized countries such as China, the United States and India (IEA, 2017). Also, the use of RES presents a significant potential for electricity generation in developing countries, in which, the demand for energy grows gradually (Kim et al., 2017).

Colombian electricity generation is mainly based on hydroelectric plants (66%) and gas and thermoelectric coal plants. In order not to depend on hydrological fluctuations and dependence on fossil fuels, the country needs to implement non-conventional RES (NCRES) for the generation of electricity. Although the National Energy Plan (UPME, 2015) promotes the use of NCRES to expand electricity generation supplies, and promotion and incentive mechanisms such as those established by law 1715 have been implemented, NCRES currently only represents 0.7 % of energy in Colombia (UPME, 2017).

In recent years, thermoelectric devices (TED) have become a promising alternative for the generation of energy. Due to the different advantages of these devices, they have been considered as one of the most promising technologies, and the closest to commercial, industrial and domestic applications (Young et al., 2017, Karvonen et al., 2016). Among the advantages of the TED is its ability to directly convert thermal energy into electrical energy, its compact size, its absence of moving parts, its moderate performance and being environmentally friendly (Sahin and Yilbas, 2013; Champier, 2017). For this reason, TEDs are still being researched to improve their applications in processes such as the recovery of lost thermal energy, the production of energy in extreme environments, the generation of electrical energy in remote areas, among others.

This study develops a presentation of the basic principles of operation of the TED, the materials that constitute it and an exhaustive number of examples that show the application of the TEG in the recovery of residual heat in transport and industry, the generation of electricity in extreme conditions and domestic uses. Thus, as the social and economic impact that can have both in developing and developed countries. The objective is to demonstrate the potential and versatility that TEDs have as a source of renewable energy that can alleviate the great energy demand of our times.

## 2. ENERGY SITUATION IN COLOMBIA

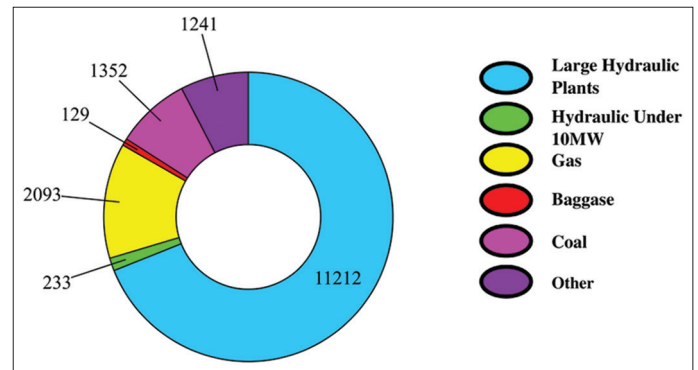
### 2.1. Energy Policies in Colombia

In Colombia, national policies for the electricity sector are administered by the Ministry of Mines and Energy (MME), through the energy mining planning unit (UPME), governed by law 143 of 1994 and by decree number 1258 of June 17 of 2013. The UPME's function is to establish the country's energy requirements and prepare the National Energy Plan and the Electricity Sector Expansion Plan, by the National Development Plan project (UPME, 2019). Other entities that make up the energy sector are: The energy and gas regulation commission (CREG), which is responsible for regulating the provision of residential public services of electric power, fuel gas and public services of liquid fuels (CREG, 2019), the national center of dispatch, in charge of the planning, supervision and control of the integrated operation of the generation, interconnection and transmission resources of the National Interconnected System (GEB, 2019) and the national operation council (CNP) whose main function is to agree on the aspects technicians of the National Interconnected System (CNO, 2019). Figure 1 shows the installed capacity for the generation of electric power in Colombia. It is observed that approximately 68.9% is generated from hydraulic power plants.

Colombia's high dependence on its hydroelectric resources puts the country at risk when periods of scarcity occur. Figure 2 shows the behavior of the generation of energy by primary energy sources between 2007 and 2016. The fluctuations in the 2009-2011 and 2014-2016 periods are the result of meteorological events such as El Niño and La Niña (Gonzalez et al., 2017). Studies indicate that this type of fluctuations tends to increase due to climate change (CorpoEma, 2010).

**Figure 1:** Composition of power generation in Colombia.

Source of data: Prepared by the authors based on data from (UPME, 2017a; XM, 2018)



Countries such as Uganda and Albania that depend on reservoirs and hydroelectric generation plants have faced continuous energy crises due to droughts and the growth of demand. The use of RES is one of the solutions that has been proposed to minimize this type of problems (UPME, 2019a). Uruguay, for example, has responded to the risk of hydroelectric plants by installing a significant amount of non-conventional renewable energy, avoiding the high levels of operation in thermal plants. In countries such as Norway, Sweden, and Finland, water power is used effectively to balance and complement the variable generation of other renewable sources (UPME, 2019a).

Based on this evidence, there is a need to look for strategies in Colombia that seek protection against the risks associated with the dependence on hydroelectric resources. The promotion of the implementation of NCRES seeks to contribute to satisfying the future growth of electricity demand and seasonal fluctuations (Macías and Andrade, 2013).

### 2.2. Strategy for the Promotion of NCRES in Colombia

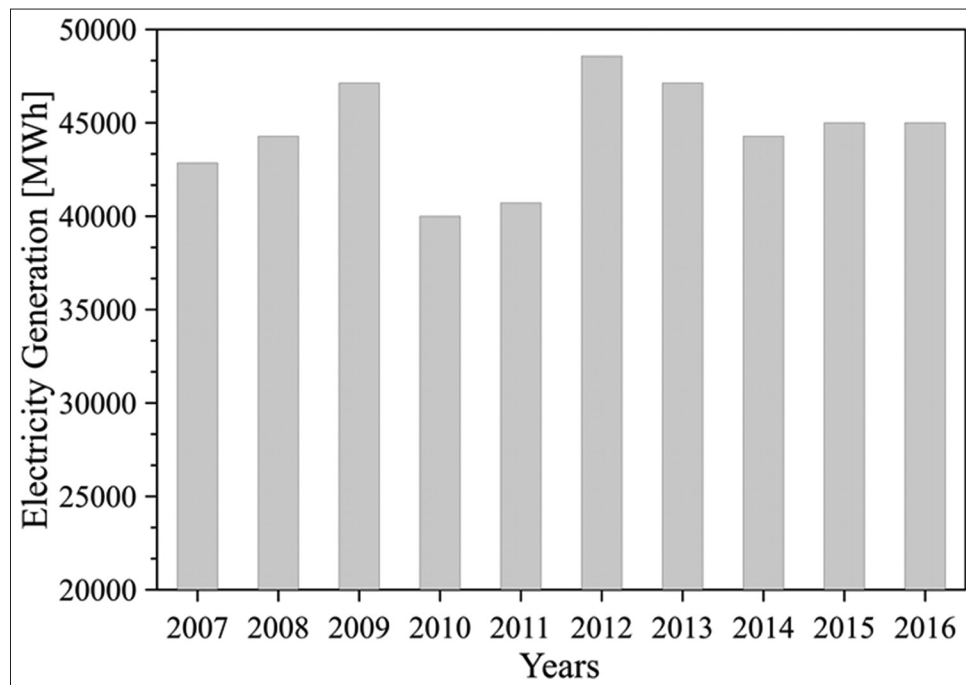
In recent years, a series of laws have been developed in Colombia to promote and facilitate the integration of NCRES into the national energy system. The enactment of Law 697 (Gobierno Nacional, 2001) establishes that the government through the MME formulated guidelines for policies, strategies, and instruments to promote the use of NCERS. In 2014, through Law 1715, incentives to renewable energy projects for companies and the market were announced. Among these incentives were: tax exclusions, tariff exemption and accelerated depreciation of assets (Gobierno Nacional, 2014).

However, to date, the impact of this law has been very limited, because the participation of NCRES in Colombia only represents 0.7% of electricity generation (UPME, 2015a).

## 3. NON-CONVENTIONAL RENEWABLE ENERGIES IN COLOMBIA

### 3.1. Photovoltaic Solar Energy

According to the Atlas of solar radiation of the UPME, regions such as La Guajira, part of the Atlantic Coast and other specific

**Figure 2:** Generation of electricity from the primary sources of Colombia

Source of data: Prepared by the authors based on data from (UPME, 2017a)

regions in the departments of Arauca, Casanare, Vichada and Meta, among others, have radiation levels above the national average that can reach the order of 6.0 kWh/m<sup>2</sup>, which is one of the best indices in the world, which can be compared to regions such as the Atacama Desert in Chile or the states of Arizona and New Mexico in the United States (NREL, 2008). Table 1 presents the average radiation values for different regions of the country.

Despite the high potential of solar energy, the lack of technical standards for the selection, configuration and installation of equipment, the difficulties in connecting small and large photovoltaic systems to the main sources of energy, the lack of financial programs intended for investment in photovoltaic energy and the absence of a regulatory framework that focuses on the use of smart grids, has led to the reduction of its applications.

### 3.3. Wind Power

Colombia has certain regions such as the department of La Guajira and a large part of the Caribbean region, as well as the departments of Santander and Norte de Santander, specific areas of Risaralda and Tolima, the Valle del Cauca, Huila and Boyacá with usable resources. For the generation of wind power, which in the specific case of La Guajira are considered to be the best in South America (UPME, 2019a). In this state, there are winds with average speeds close to 9 m/s and prevailing east-west direction (Huertas and Pinilla, 2007), which are estimated to represent an energy potential that can be translated into an installable capacity of the order of 18 GW electric (Bedoya and Osorio, 2002). Given this considerable potential, the large generating companies in Colombia, like other smaller companies and foreign firms, nowadays have stations and measurement projects concentrated in the North Coast region or La Guajira, to eventually develop wind generation projects there, in the short and medium term.

**Table 1: Average radiation values for different regions of the country**

| Region          | Average radiation day (kWh/m <sup>2</sup> ) |
|-----------------|---|
| Guajira         | 6.0   |
| Costa Atlántica | 5.0   |
| Orinoquía       | 4.5   |
| Amazonía        | 4.2   |
| Region Andina   | 4.5   |
| Costa Pacífica  | 3.5   |

Source of data: Prepared by the authors based on data from (UPME, 2015a)

However, there are barriers such as the lack of electrical infrastructure necessary to dislodge the energy produced in the interior of the country, the complexity of the negotiation processes with the communities that inhabit the region (UPME, 2019a) and, in general terms, the absence of a regulatory and regulatory framework that enables the participation of this type of energy.

### 3.4. Biomass Energy

In 2017, Colombian electricity generation totaled 793 MWh, mainly using the waste from the sugar sector (UPME, 2019a). In addition to this sector, there is potential in other sources of biomass such as agricultural residues, forest residues, energy crops, residual biomass from livestock farms and urban solid waste biomass (UIS, 2010). However, current policies do not promote the development of this type of technology.

## 4. TED

Despite the potential of solar energy, wind energy and biomass energy as sources of renewable energy in Colombia, the absence of a technical and operational regulation to guide the development of these technologies, the lack of networks close to the areas of

greater potential and the difficulty of installation in some regions of the country for the damage to indigenous communities, has slowed the development and implementation of these sources. There is a need to look for alternatives that are easier to install and generate less impact on their environment. In recent years, TEGs have attracted the attention of the world. Because of their great number of advantages and their versatility in the fields in which they can be applied, they have become a promising source of unconventional renewable energy.

### 4.1. Basic Principles of TED

The (TED) are solid state devices that directly transform thermal energy from a temperature gradient into electrical energy (Hamid et al., 2014). This technology was implemented by Thomas Johann Seebeck in 1821 (Riffat and Ma, 2003). Seebeck reported that potential thermoelectric energy could be developed in the presence of a temperature difference between two different materials. Consequently, this phenomenon was referred to as the “Seebeck effect.”

Among the advantages of the TEG we can mention its absence of moving parts, it does not generate pollutant emissions, without operating or maintenance costs, without chemical reactions with the environment (that is, respectful with the environment) and its compact size (He et al., 2015; Dai et al., 2011; Tie and Wei, 2013).

The fundamental principle of the TEG is based on the concept of the Seebeck effect, where the voltage generated is directly proportional to the temperature gradient (Gould et al., 2008), as shown in the following equation:

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

Where  $\alpha$  is the Seebeck coefficient of the materials that make up the thermoelectric (TE), and  $\Delta T$  is the temperature difference between the two surfaces of the TED.

The TEDs are internally constituted by semiconductors of type p and n, where the P-type has excess holes, and the n-type has surplus electrons to carry the electric current (Figure 3). When heat flows from the hot surface to the cold surface through the thermoelectric material, the free charges (electrons and holes) of the semiconductors are also moving. This movement of load converts thermal energy into electrical energy (Prabhakar et al., 2018).

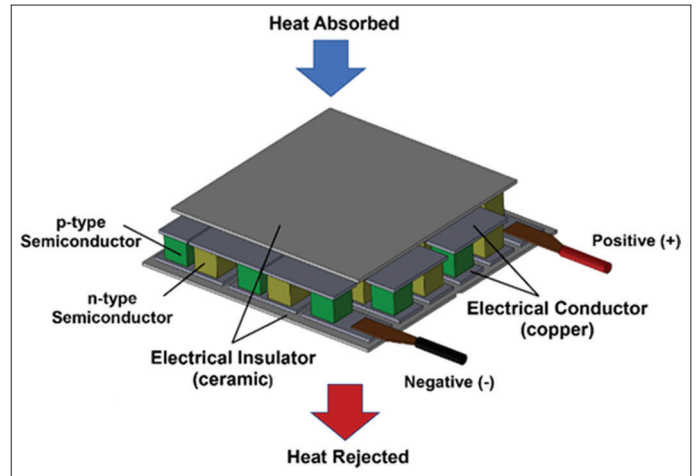
Figure 4 shows the thermal energy rate of its two surfaces,  $\dot{Q}_h$  and  $\dot{Q}_c$  (hot side and cold side). Each of these rates can be expressed as (Lee, 2013):

$$\dot{Q}_h = n \left[ \alpha_{pn} T_h I - 0.5 R_{pn} I^2 + K_{pn} (T_h - T_c) \right] \tag{2}$$

$$\dot{Q}_c = n \left[ \alpha_{pn} T_c I + 0.5 R_{pn} I^2 + K_{pn} (T_h - T_c) \right] \tag{3}$$

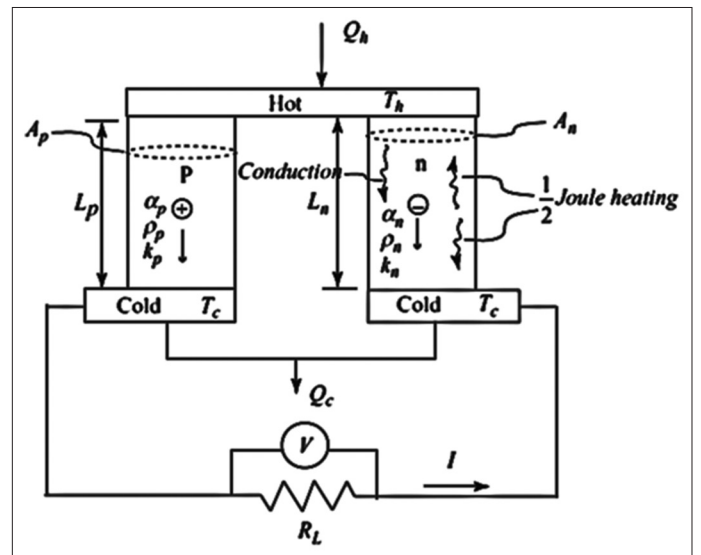
Where  $\alpha_{pn}$  is the Seebeck coefficient,  $K_{pn}$  is the thermal conductance,  $R_{pn}$  is the electrical resistance for a couple of semiconductors P-N

Figure 3: Schematic diagram of thermoelectric devices



Source of data: Prepared by the authors based on data from (Lee, 2013)

Figure 4: Schematic view of p-n junctions in TED



Source of data: (Lee, 2013)

and is the number of thermoelectric unit couples in one module. The values of  $\alpha_{pn}$ ,  $K_{pn}$ ,  $R_{pn}$ , can be obtained in the following way:

$$\alpha_{pn} = \alpha_p - \alpha_n \tag{4}$$

$$K_{pn} = \frac{A(k_p + k_n)}{L} \tag{5}$$

$$R_{pn} = \frac{L(\rho_p + \rho_n)}{A} \tag{6}$$

The power generated is given by:

$$P = n(\dot{Q}_h - \dot{Q}_c) \tag{7}$$

The efficiency (defined as the ratio between the electric power produced and the rate of thermal energy entering the hot face) of a TEG can be approximated by the following relationship for an optimal electric charge (Rowe, 2018):

$$\eta = \frac{P}{\dot{Q}_h} = \frac{T_H - T_c}{T_h} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_c}{T_h}} \tag{8}$$



Where  $ZT$  is the merit number, which can be expressed as:

$$ZT = \frac{\sigma_{pn} [\alpha_{pn}^2]}{\lambda_{pn}} T \tag{9}$$

Where  $\alpha_{pn}$  is the electrical conductivity and  $\lambda_{pn}$  is the thermal conductivity. From this number, you can determine the efficiency of the materials that make up a TED (Figure 5).

Researchers and manufacturers are in a constant search for new materials that can improve the capacity of TEG in three aspects:

- Increase the merit number ( $ZT$ ).
- Increase the operating range of the materials (that is, work at higher temperature ranges).
- Reduce the cost of the material.

#### 4.2. Materials

For years, the only modules available for industrial applications (except space) at a reasonable price were the bismuth telluride modules ( $\text{Bi}_2\text{Te}_3$ ). However, the low abundance of bismuth and tellurium (Haxel et al., 2002) in the earth's crust and oceans have limited the development of TEG based on  $\text{Bi}_2\text{Te}_3$ .

Manufacturers' research laboratories have been looking for cheaper and environmentally friendly replacement materials that can be produced commercially in large quantities.

Table 2 summarizes the properties of all these modules: The materials used, the appropriate temperature difference between the two sides of the modules, the maximum power obtained for this difference, the availability of the module and the maximum continuous working temperature. As you can see, many mineral TEGs are available or will be available soon. Its new properties, such as its range of operation, price, weight,

and non-toxicity, open interesting perspectives for large-scale industrial development.

### 5. APPLICATIONS

Taking into account the conditions in which the TED is used and the nature of the heat source, a classification of the applications of the TED has been made in the following categories.

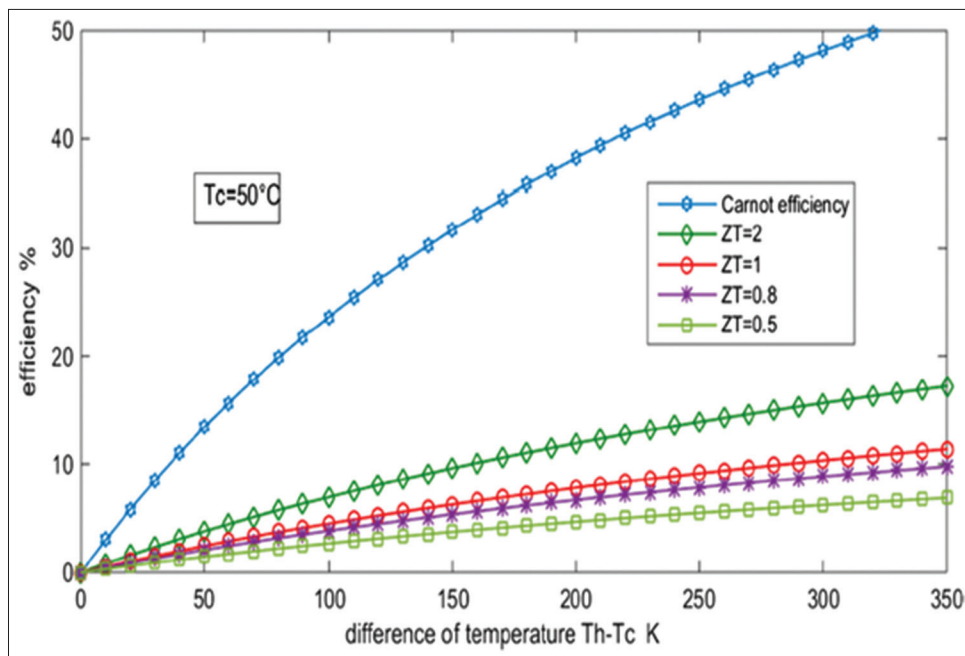
#### 5.1. Production of Electricity in Extreme Environments

These applications require a highly reliable power source for long periods. The climatic conditions can be extreme, very hot or very cold, very humid or very dry. The maintenance should be as low as possible. Reliability for these cases is the most important consideration. In remote areas, the use of TEG can produce electricity reliably and with minimal maintenance.

Currently, the Gentherm company is the world leader in the production of electricity generators for remote areas (GENTHERM, 2019). The company has existed for 30 years and produced about 22,000 installations. This technology allowed the feeding of a communication station that provided Internet access to five school districts in Grant County. Given the remote location of the station and the winter periods that precluded the use of solar panels, opted for the use of the TED, because, due to the absence of moving parts, did not require maintenance and also supported the low temperatures in the area (GENTHERM, 2019a).

These TEGs use the heat produced by the combustion of natural gas, butane or propane. The burner heats one side of the TE modules and the other side of the finned modules is cooled by natural convection. They are used in gas pipelines, wells, offshore

Figure 5: Typical values of TE efficiency for different values of  $ZT$



Source of data: (Champier, 2017)

**Table 2: List of TE modules and their properties**

| Manufacturer                   | Materials                                | Temperature difference $\Delta T$ | Power | Status      | Maximum temperature | Information, outlook   |
|--------------------------------|--|-----------------------------------|-------|-------------|---------------------|--|
| OTEGO                          | Organic TED                              | Small temperature gradients       |       | Coming soon | 130°C               | Environmentally friendly, low cost, easily scalable.               |
| Alphabet Energy                | p-type tetrahedrites<br>n-type magnesium | 300 K                             | 9.2 W | Available   | 600°C               | Tetrahedrite is a naturally-occurring p-type mineral.              |
| Hotblock Onboard               | Silicon-based alloy                      | 500 K                             | 3.6 W | Available   | 600°C               | Environmentally-friendly, low cost, availability of raw materials. |
| Evident Thermoelectric         | Half-Heusler                             | 500 K                             | 15W   | Coming soon | 600°C               | Environmentally-friendly, low cost, availability of raw materials. |
| Shanghai Institute of Ceramics | Skutterudites                            | 510 K                             | 25W   | Coming soon | 600°C               | Environmentally-friendly, low cost, availability of raw materials. |

Source of data: Prepared by the authors based on data from (OTEGO, 2019; Alphabet Energy, 2019; Hotblock, 2019; Champier, 2017)

platforms, telecommunications sites and for security surveillance and monitoring (Champier, 2017).

## 5.2. Recovery of Residual Heat

An estimate made by the Lawrence Livermore National Laboratory (LLNL, 2019) indicates that in the United States in 2014, 38.4 Quads (one Quads is approximately 293 million MWh) were generated by primary energy sources, from which 25.8 were released. Quads to the environment in the form of heat. In an automobile, in general, the energy used in gasoline combustion engines is decomposed by 25% for mobility, 30% in the coolant, 5% in other parasitic losses and 40% in the exhaust gases (Kim et al., 2017a). For diesel trucks that use 100 kW of fuel power, this represents 30 kW of heat loss in the exhaust gases. Converting this lost energy into electricity, even with an efficiency of 3%, could represent 900 W of electricity. According to the Fiat Research Center, 800-1000 W would mean a reduction of 12-14 g/km of CO<sub>2</sub> emissions.

The above facts show that residual heat in both industrial processes and the vehicular sector represents a potential source for the generation of energy.

### 5.2.1. Heat recovery in the industry

The industry is a field where heat is often a by-product of the process. Although part of this heat is used to reheat networks or produce electrical energy, much of the heat is lost in the atmosphere.

Several forms of waste heat recovery in the industry has been investigated through the TEDs. In 2009, KELK Ltd implemented a thermoelectric generation system in a carburizing furnace of Komatsu Ltd., Awazu plant. Using a TED consisting of 16 Bi<sub>2</sub>Te<sub>3</sub> modules and a heat exchanger, an electrical output power of 214 W was achieved, representing an efficiency of 5% (Kaibe et al., 2012).

The steel industry produces a large amount of waste heat, mainly the radiant heat of steel products. JFE Steel Corporation Corporation (JFE) in Japan has implemented a TEG system that produces about 10 kW, using the radiant heat from the casting slabs (Kajihara et al., 2015).

Cement production is an industrial process that releases a large amount of heat to the atmosphere. It has been estimated that this

process dissipates approximately 10-15% of energy through the surface of the rotary kiln. Using the elaboration of a mathematical model, it was predicted that the use of the TED would generate about 210 kW. This is equivalent to an energy contribution of 2% (Luo et al., 2015).

These different studies in the industry show that TEGs have two main advantages over other means of recovery:

- Ease of installation in places where other conventional sources would be difficult.
- Do not require any or little maintenance, which considerably reduces costs.

### 5.2.2. Heat recovery in the engine exhaust

As mentioned above, combustion engines despite the improvements implemented over the years still presented a low thermal efficiency. Only 25% of the fuel's energy potential is used for mechanical work, and 40% of this potential is wasted in the atmosphere using the exhaust gases. For this reason, it has looked for ways to recover this lost energy.

The use of TEDs in Porsche, trucks and passenger cars and military vehicles has been studied (Rowe, 2016). The companies BMW, BSST, and Visteon, designed a system (Figure 6) for the recovery of waste heat from the exhaust gases. With the recovered power a reduction of 8-12.5% of the fuel was achieved (LaGrandeur et al., 2005).

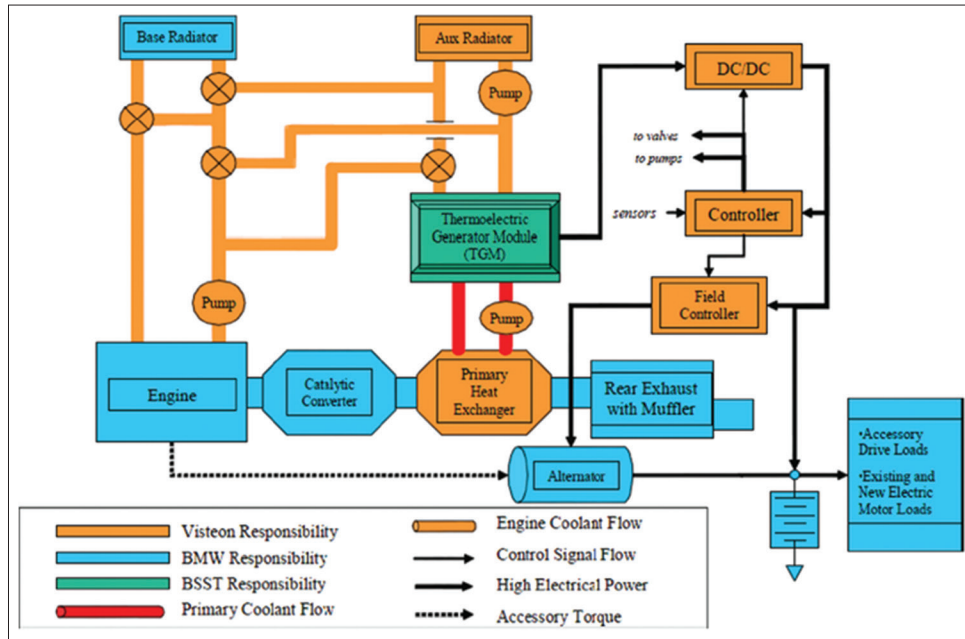
The use of TED coupled to a heat pipe-assisted heat exchanger (HP-TEG) has been proposed for the recovery of residual heat from automobile exhaust. The power output and the pressure drop obtained were 13.08 W and 1657 Pa, respectively, with an energy generation efficiency of 2.58% (Cao et al., 2018).

Projects such as HEATRECAR, seek to reduce fuel consumption through the recovery of waste heat using TED in light trucks. The yields achieved by the TEG show an improvement in fuel savings of 3.9% (6.7 g CO<sub>2</sub> reduction/km) (European Commission, 2019).

## 5.3. Domestic Uses

Due to the energy conversion characteristic of the TED, virtually any heat source can be chosen as a source of electrical generation. For example, households that frequent the use of stoves, biomass or some heating source have great potential to use TEDs.

**Figure 6:** Block diagram for waste heat recovery power generation system



Source of data: (LaGrandeur et al., 2005)

Below are domestic uses of TED in developed and developing countries.

**5.3.1. TEG in developed countries**

In developed countries, the use of high-performance wood stoves is increasing for economic and environmental reasons. These stoves need electronic components (sensors, fans, valves, and microcontrollers) to control combustion to meet the minimum emission requirements. There are cases of houses isolated from the electrical connection and even homes that despite having an electricity supply are affected by the presence of power cuts during winter periods.

For these reasons’ companies like “Bioenergy 2020+” that develops CHP combustion units with wood pellets, have arranged TED around the combustion chamber. The source of cold is the outside air. Several prototypes have been produced: the TEG 250 equipped a 10-kW boiler and produced 170 W, the TEG 400 cooled by ambient air, an 8-kW stove and provided 100W, and the water-cooled TEG 400 was installed in a boiler. 12 kW and provided 300 We (Friedl et al., 2009). TEDs could also be developed to improve the efficiency of old stoves. The company Ecofan sells heat fans for heaters of stoves (ECOFAN, 2019). The airflow created by the fan distributes the hot air from the stove more evenly in the room. The addition of the TEDs can allow the production of electric power to support the use of the fan without the need for electrical connection (Codecasa et al., 2012).

**5.3.2. TEG in developing countries**

In developing countries, an estimated 1.2 billion people (17% of the world’s population) do not have access to the electricity grid (0016), despite their electrical needs. Biomass is the main source of energy. In these rural areas, wood burns with very low thermal efficiency: <10% for three-stone stoves and only about 35-40% for rocket stoves and electric stoves.

Given the remoteness of many villages and homes, the installation of power lines would be very expensive. Also, in these types of settlement, electricity is mainly used for a few hours at night, since they usually do not have commercial or industrial activities. The above makes it clear that the electrical connection would not be a viable solution.

The production of energy using autonomous sources is possibly the only viable solution. Although solar energy seems attractive, it has the disadvantage of requiring large storage capacities for periods without sun. The TED could provide some watts for lighting, to charge mobile phones and electric power extractors (Champier, 2017).

Some laboratories have researched the installation of TE (Bi2Te3) modules in kitchens or stoves. They also tried to improve heat transfer, by using heat pipes. The maximum power reached in these studies was approximately 3.4 W (Nuwayhid and Hamade, 2015).

Another study presented a multipurpose stove with TED. A heat exchanger was used between the hot combustion gas and the air in the room. The maximum power obtained is approximately 7.88 W with wood, manure or peat, with an average overall efficiency of the stove of approximately 60% (Najjar and Kseibi, 2016).

**5.4. Solar TED (STED)**

STED are solid state heat engines that generate electricity from concentrated sunlight. STEGs have several advantages compared to traditional solar generators. STEGs are solid state devices with no moving parts, which significantly increases reliability and lifespan. Also, STEGs are a scalable technology that can be used for small or large scale applications. While photovoltaic energy is limited to the fraction of incident solar radiation above the band gap, STEGs use a larger portion of the solar spectrum (Baranowski et al., 2012).



The Massachusetts Institute of Technology (Kraemer et al., 2011) has demonstrated a solar thermal conversion technology. The developed STEG reached a maximum efficiency of 4.6% in solar conditions of 1 kWm<sup>-2</sup>. With the current TE materials, the total efficiency of 14.1% is possible with a hot side temperature of 1000°C and a solar intensity concentration of 100, including a non-ideal optical system (Baranowski et al., 2012).

STEDs can be a cost-effective alternative to photovoltaic energy for residential energy supply in remote areas (Moumouni, 2015).

## 6. POTENTIAL TED APPLICATION IN COLOMBIA

Many of the industrial processes in Colombia generate energy waste in the form of sensible heat, latent, radiation or convection that are discharged from the system and dissipated in the environment. The recovery of waste heat is one of the methods to improve the efficiency of the process and reduce the energy intensity of industrial facilities. Given that this type of energy is susceptible to being recovered through the TED, the Colombian industrial sector becomes a potential source to implement the TED.

For example, the Colombian ceramic industry has been considered as an industry that has not had great technological advances (Molina et al., 2017). This industry uses ovens in its manufacturing process in which the gases inside the furnace chamber go around high temperatures (200-100°C) (Medina and Jaramillo, 2019). In the brick industry, it also presents a waste of the caloric energy of its process. As in the ceramic industry, brick building processes require medium at high temperatures, between 900 and 1000°C (Camelo, 2015). In the Antioquia regions and mainly in the eastern region (central Magdalena) there are companies dedicated to the production of lime and cement, due to the deposits of the region. Despite being a relatively inexpensive process, many of the systems used are of low efficiency (Castaño et al., 2015). The use of the TED in this process could increase its overall efficiency.

The operating conditions of these industrial processes make them a potential application for TEDs. Table 3 shows a list of other processes in which heat is discarded and that, given their temperature conditions, TED could be applied.

## 7. CONCLUSIONS

Colombia has resources at the national level for the generation of solar, wind and biomass energy. However, the use of these energy sources represents only 0.7% of the total energy generation. Despite the creation of new regulations and laws that promote and encourage the development of non-conventional sources of energy, there are still barriers that prevent their increase. The high investment costs, the lack of human capital with knowledge in these technologies and general policies focused on conventional sources, are the main difficulties for the development of these energy sources.

In this review, the great potential of TED as an unconventional source of renewable energy was observed due to its considerable

**Table 3: Residual heat sources**

| Category                | Heat source             | T (°C)   |
|-------------------------|-------------------------|----------|
| Temperature (>650°C)    | Copper refining furnace | 760-815  |
|                         | Incinerators            | 650-1450 |
|                         | Cement Clinker          | 620-730  |
| Temperature (230-650°C) | Boiler exhaust steam    | 230-480  |
|                         | Engine exhaust pipes    | 315-600  |
|                         | Cooling system in ovens | 425-650  |
|                         | Turbine exhaust gases   | 370-540  |

Source of data: Prepared by the authors based on data from (Tchanche *et al.*, 2011)

advantages over other sources of renewable energy and its wide variety of applications.

The continuous development of the materials that make up the TED has allowed its use in higher ranges of temperatures and turn made with low-cost materials. This motivates the use of TED despite its relatively low efficiency. Studies show that TEDs are a viable way to recover the heat generated in industrial processes. Given its simplicity, compactness and low maintenance, it can adapt to various types of surfaces. Its use has been demonstrated in the iron and steel industries, cement production and industries with carburizing furnaces.

The waste heat from the exhaust gases in the transport sector has become a striking source for using TEDs. In addition to producing an amount of electrical power through TED installed in the exhaust system of the engine, allows reductions in emissions such as CO<sub>2</sub>.

In both developed and developing countries, the various studies and examples presented show that TEGs are a reliable alternative to provide some electricity when grid connection is not possible. This ability to produce some electricity also improves the efficiency of the heat generating devices mildly or constantly.

Due to the variety of industrial processes in Colombia that are sources of residual heat and high temperatures, such as the iron and steel industries, ceramics and cement production, the implementation of the TED can become an important source of renewable energy, which in addition to generating Electric power allows to increase the efficiencies of these industrial processes. In addition to this, the STED could generate reliable electrical supply systems that allow powering wireless communication devices, maintenance systems and monitoring in remote and isolated regions of Colombia.

The potential of the variety of applications described in this review shows that in the TEG can be used virtually any situation of industry or domestic use that has some source of energy.

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