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Review

Innovative Technology Strategies for the Sustainable Development of Self-Produced Energy in the Colombian Industry

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Abstract: This research studies the current state of the Colombian industrial sector, which is focused on self-generation processes. The study's objective is to search for viable technological strategies that strengthen this particular sector's competitiveness and sustainable development. The analysis shows that internal combustion engines represent 49% of the technologies used for self-generation. The main fuel used in the sector is natural gas, with a percentage of 56%. The lack of strategies for the use of residual heat and technological inefficiencies caused a loss of 36% in the energy used in the Colombian industrial sector. Thermoelectric generators are a feasible way to recover energy from exhaust gases in engines used for self-generation. Additionally, they allow a 4% reduction in fuel consumption and an improvement in the engine's energy efficiency. The use of hydrogen as fuel allows a 30% reduction in polluting emissions, such as CO_2, CO, HC, and particulate matter. Hydrogen production processes, such as water electrolysis, allow the participation of Colombia's solar energy potential, leading to sustainable hydrogen production, efficiency (60–80%), and a lower economic cost. In general, the application of thermoelectric generators and the use of hydrogen gas allow the improvement of the Colombian industrial sector's environmental, social, and economic aspects due to greater competitiveness and the reduction in emissions and operating costs.

Keywords: waste heat recovery; hydrogen production; sustainability; energy; engine

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1. Introduction

The constant industrial growth, and the modernization of countries has resulted in a negative impact on the environment [1]. Despite rapid economic development due to the different industrial sectors in recent years, there has been a high consumption of energy resources and high environmental pollution [2,3]. According to reports in the literature, the extraction of natural resources has tripled in the last four decades. Additionally, greenhouse gas emissions have increased by 1.5% each year. The effects of industrial activities are reflected in an increase in global temperature and changes in the planet's climate. The foregoing have encouraged efforts for sustainable and environmentally friendly industrial growth, in different fields of the economic sector, and applying different methodologies (experimental and numerical models) [4,5].

In recent years, organizations have required greater responsibility for their activities. This is because economics and competition are no longer the only relevant considerations. The issues that involve social and environmental aspects also affect the behavior of organizations [6]. Among the strategies of the organizations are the cleaner production, sustainable manufacturing, and management of the green supply chain [7]. All of the above are associated with sustainable development, defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [8]. Under this scenario, organizations must seek sustainable growth based on better management of energy resources, which will enable an adequate quality of life for future generations. Another concept associated with sustainable development is innovation as a key to improving sustainability. Research indicates that sustainability must be approached from innovation approaches [9]. However, in practice, changes towards sustainable processes are considerably slow, which implies a greater need for investment and projects in the industrial sector [10].

At present, the trends seek the greater integration of renewable energies and the reduction in the use of energy sources derived from hydrocarbons. The constant increase in the demand for energy due to economic growth and the increase in urbanization in countries makes the transition to renewable energy sources more urgent, which requires a reduction in the presence of fossil fuels and a greater integration of renewable energies [11–15]. Due to the above, global decarbonization in the different economic sectors is necessary to mitigate the environmental impact caused by polluting emissions [16]. Despite their environmental impact, carbon-based fuels account for 85% of energy consumption worldwide [17,18]. This means that 90% of polluting emissions originate from fossil fuel combustion [19,20].

Energy transition is one of the most crucial concerns in recent years. Alternative fuels have been proposed to achieve this objective, among which hydrogen stands out [21]. This fuel stands out for being a clean energy carrier due to its absence of carbon content [22]. Additionally, hydrogen is the most abundant element on earth, with a calorific value of less than 120 MJ/kg, considerably higher than other fuels, such as gasoline and diesel. The sustainable characteristic of hydrogen as a fuel depends on the production process since it must be economically viable and not affect the environment [23]. Due to this, researchers have sought hydrogen production processes that reduce CO_2 emissions and economic costs [24]. In general, searching for hydrogen generation systems with low carbon emissions, low costs, and high efficiency is necessary to satisfy demand [25].

Another strategy focusing on mitigating global warming and climate change is better energy management in production processes. In recent years, waste heat recovery is a promising approach to improve energy efficiency, especially in internal combustion engines [26]. In the particular case of internal combustion engines (ICEs), approximately 30% of the chemical energy of the fuel is wasted in the environment [27]. Using waste heat from engine exhaust gases saves fuel consumption significantly [28]. This directly contributes to energy and operational cost savings.

The technologies described above focus on waste heat recovery and use hydrogen as a fuel, contributing to a carbon-free energy transition in the coming decades. However, at present, different technologies can be used for waste heat recovery, as well as low-carbon technologies for the production of hydrogen gas. Despite the various technology options that focus on waste heat and hydrogen production, no studies that identify the most promising technologies considering the characteristics of the Colombian industrial sector have been conducted. Similarly, there is not an evaluation of the impact of these technologies on the sustainable development of the industry in Colombia. Due to this situation, the present research analyzes the energy recovery and hydrogen production technologies that present greater viability to be implemented in the self-generating industrial sector in Colombia. The objective is to evaluate the impact of integrating these technologies in the Colombian industrial sector's environmental, social, and economic aspects. This is in order to identify strategies that favor the progress and sustainable development of the Colombian industry.

2. Methodology

For the development of the research, a review of the literature was carried out following the methodology proposed in Figure 1.

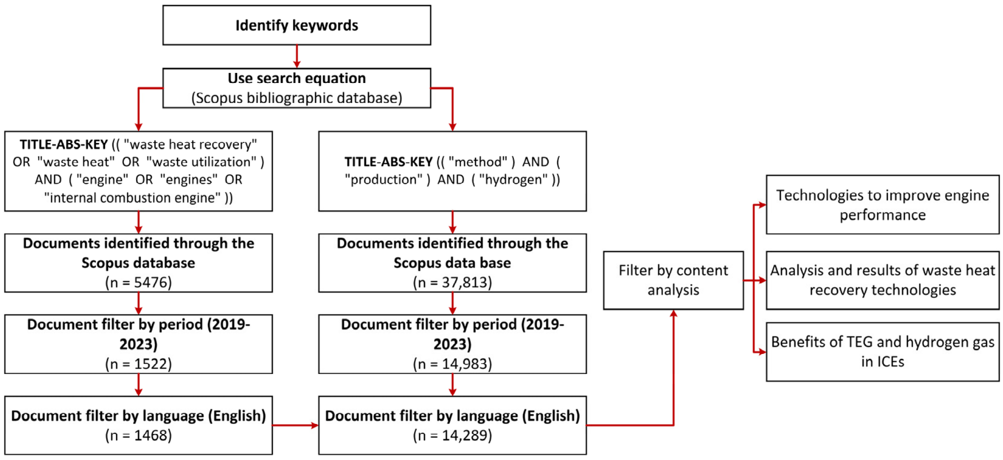

Figure 1. Literature review procedure.

The first step in the proposed methodology involved identifying the documents from the Scopus bibliographic database. The search engine ScienceDirect Topics was used to define keywords to identify the words used in the scientific vocabulary. Based on the above, different search equations were established, which are shown below:

TITLE-ABS-KEY ((“waste heat recovery” OR “waste heat” OR “waste utilization”) AND (“engine” OR “engines” OR “internal combustion engine”)) (1)

TITLE-ABS-KEY ((“method”) AND (“production”) AND (“hydrogen”)) (2)

The Scopus data searches were restricted by applying a period filter (2019–2023) and a language filter (English). The number of documents selected from the search equations are shown in Figure 1. Subsequently, the selected documents were filtered taking into account the information provided in the title, abstract, introduction, results, and conclusions. Additionally, the papers were grouped into review articles and research articles. Finally, the documents most related to the proposed topic were used for the construction of Section 3 (technologies to improve engine performance), Section 5 (benefits of TEG and hydrogen gas in ICEs), and Section 4 (analysis and results of waste heat recovery technologies) of the present research.

3. Characteristics of the Self-Generating Industrial Sector

Currently, a large part of the industrial sector in Colombia is self-generating electricity. The primary energy sources and types of technologies used for self-generation are shown in Figure 2.

The results described in Figure 2b show that the main energy source is the use of natural gas as fuel, with a share of 56%, followed by water sources (29%) and coal (15%), respectively. In the particular case of Colombia, natural gas is used in internal combustion engines (ICE) coupled to electric alternators (also known as Genset) [30]. Studies carried out by the UPME indicate that the Colombian industrial sector has an installation capacity with a self-generation potential of 234 MW.

The analysis of the types of technologies (see Figure 2a) shows that ICEs are the main way for self-generation in Colombia, covering an installation capacity of 49% compared to all available technologies. This demonstrates the relevant role of ICEs in the Colombian productive sector. Additionally, the power of this equipment can reach up to 10 MW, which implies high fuel consumption rates and high waste heat flows due to ICE exhaust gases [31]. Energy studies published by UPME (Mining and Energy Planning Unit) indicate that of the total energy consumed by the industrial sector, only 64% is converted into useful energy [32]. The remaining 36% is not used due to inefficiencies associated with the intrinsic nature of the energy processes and the technology of the equipment used. This energy waste represents an economic loss of USD 6.6 billion, which represents a high savings potential for the Colombian industrial sector through the implementation of technological improvements [33].

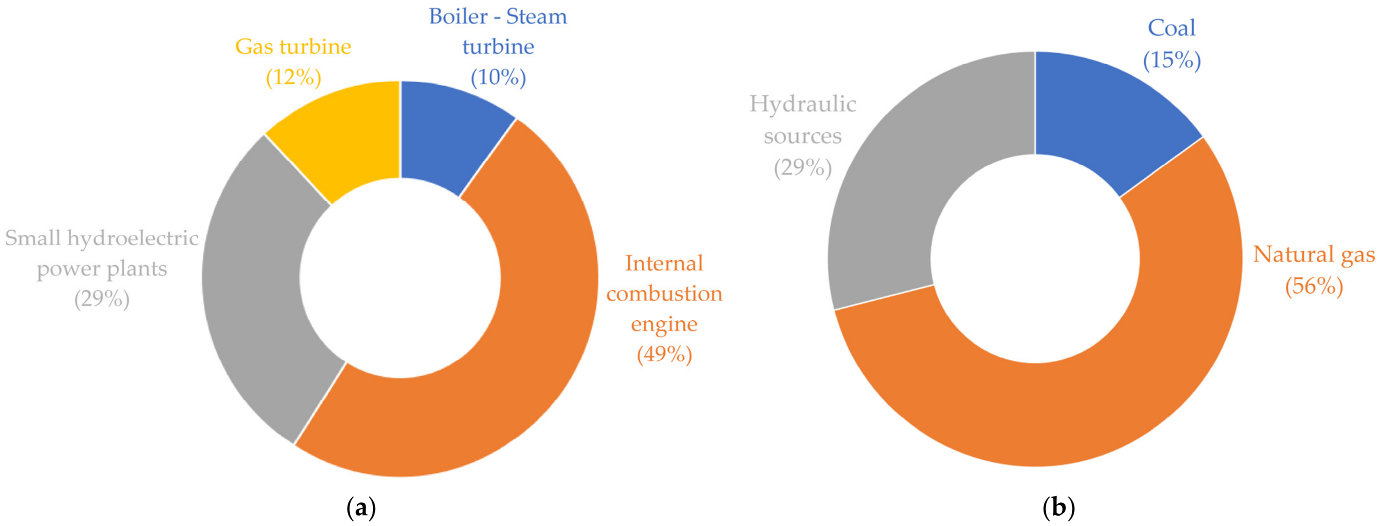

Figure 2. Self-generation in the Colombian industrial sector: (**a**) Type of technologies; (**b**) Energy sources. Source: image created by the author based on data from [29].

Part of the percentage of energy wastage in the industrial sector is associated with the use of internal combustion engines. Although these types of thermal machines have a relatively high thermal efficiency, they cannot completely transform the chemical energy of the fuel into useful mechanical power. In general, internal combustion engines transform 38% of the fuel energy into mechanical work, 25% of the energy is lost in the cooling and lubrication system, and the friction processes of the engine consume 7%. The remaining 30% is wasted in the atmosphere through exhaust gases [34]. Due to this situation, it is evident that in the self-generation processes in the Colombian industrial sector there is a high rate of unused residual energy products of the combustion gases in the ICEs, which defines a gap that must be addressed from sustainable innovation in order to mitigate the environmental impact and minimize the operational, economic costs of the industrial sector in Colombia.

The efficiency of ICEs can be significantly improved through the use of alternative fuels. Specifically, hydrogen figures are a crucial alternative for transitioning to cleaner fuels. Hydrogen is expected to play a significant role in the future and replace fossil fuels to some extent by becoming the energy carrier par excellence [35]. Currently, hydrogen represents a potential solution to meeting the energy demand. It could mitigate and even eliminate the problems linked to fuel burning by constituting an affordable, efficient, reliable, and clean technology. This option has significant advantages, such as its abundance in the universe and its energy per unit mass, which is 2.63 times higher compared to gasoline [36]. Another alternative that has attracted attention in recent years is waste heat recycling. In the particular case of internal combustion engines, the use of waste heat from exhaust gases allows both a decrease in environmental pollution and a significant improvement in energy efficiency [37].

4. Technologies to Improve Engine Performance

4.1. Waste Heat Recovery Technologies

Waste heat recovery is one of the most effective strategies to take advantage of the waste heat emitted by internal combustion engines [38,39]. This waste heat is generally released into the environment. The utilization of this wasted energy would imply a reduction in pollutant emissions and fuel consumption. Additionally, it favors the reduction in the economic costs associated with the operation and facilitates compliance with environmental protection regulations [40]. In ICEs, waste heat comes mainly from the exhaust gas recirculation (EGR), the exhaust system, and the engine radiator. These sources are possible candidates for applying waste heat recovery technologies [41]. Figure 3 shows the main methods used in ICEs for waste heat utilization.

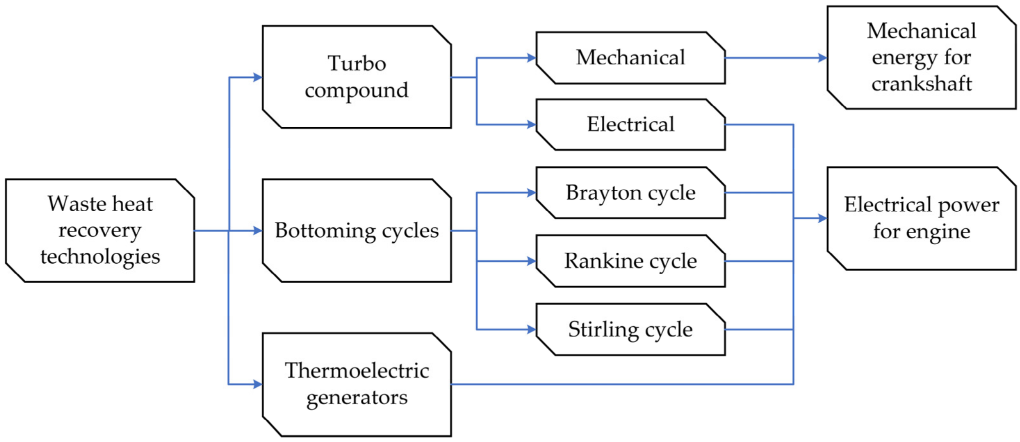

Figure 3. Waste heat recovery technologies in ICEs. Source: image created by the author.

4.1.1. Electric Turbochargers

Electric turbochargers (ETC) are electromechanical systems connected to a turbocharger shaft. These types of systems involve using turbines to capture waste heat from exhaust gases and convert it into electrical energy through a generator. Studies indicate that ETC can be used to improve turbocharger performance or as an energy recuperator [42]. A schematic of an ETC is shown in Figure 4.

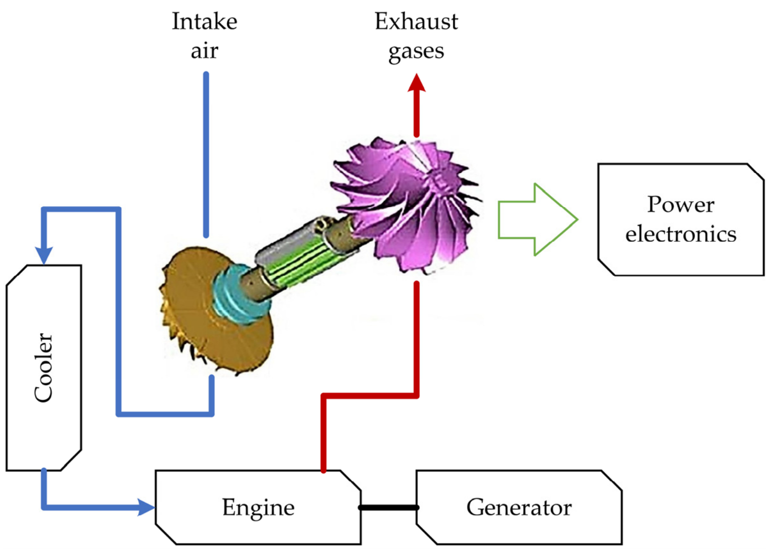

Figure 4. Electric turbochargers. Source: image created by the author.

The ETC systems' turbogenerators are designed to withstand the high-temperature conditions of the exhaust gases of ICEs. The use of electric turbochargers allows reducing fuel consumption, as well as increasing the availability of electrical energy to feed the ICEs subsystems [34]. The electrical energy obtained from the turbine is normally used to power the electrical components and charge the vehicle's battery. In general, the application of ETC can lead to an increase in efficiency between a range of 3–10%.

4.1.2. Organic Rankine Cycle

The organic Rankine cycle (ORC) is considered a viable solution for transforming waste heat from exhaust gases into useful energy [43]. The ORC consists of four main elements: feed pump, evaporator, expansion valve, and condenser, as shown in Figure 5.

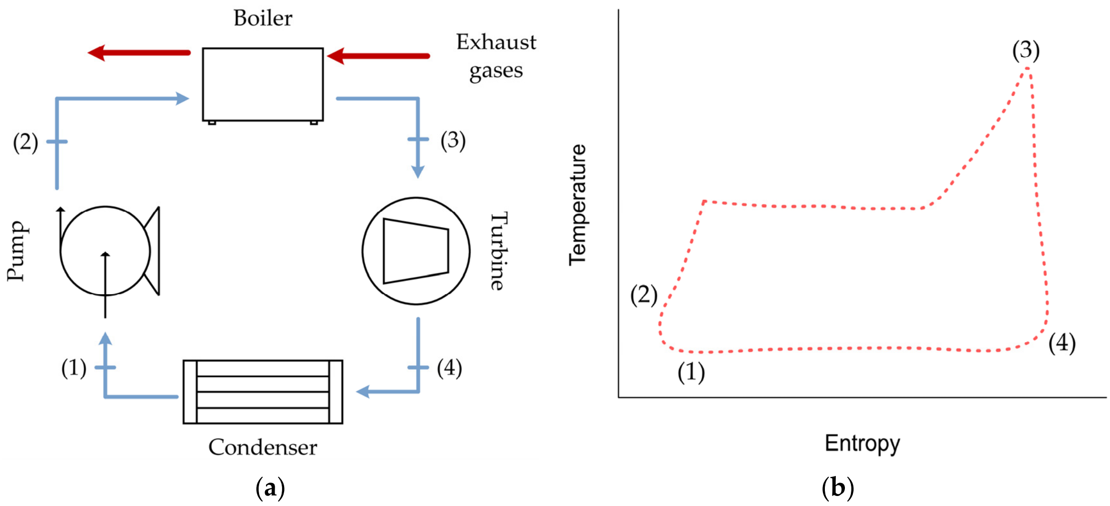

Figure 5. Organic Rankine cycle diagram: (**a**) Components; (**b**) Curve T vs. S. Source: image created by the author. $1 \rightarrow 2:$ The fluid (liquid) is compressed isentropically. $2 \rightarrow 3:$ The fluid (liquid) is heated and vaporized in contact with the hot source. $3 \rightarrow 4:$ The vapour is expanded isentropically in an expander. $4 \rightarrow 1:$ On leaving the turbine, the fluid is cooled and condensed in contact with the cold source.

During the thermodynamic cycle, the exhaust gases bring heat into the system to bring the working fluid into a gaseous state. Subsequently, the fluid is directed to a turbine to extract mechanical work from the fluid [44]. In general, the operating principle of ORCs is similar to conventional RCs. However, ORCs use high molecular weight organic liquids, facilitating the liquid–vapor phase change at relatively low temperatures. Studies indicate that ORC systems can operate with a thermal efficiency of 10 to 25% [45]. This result is a consequence of the low temperature at which the ORC operates.

4.1.3. Thermoelectric Generators

In recent years, thermoelectric generators (TEGs) have been used for waste energy recovery in internal combustion engines. TEGs are devices that have the ability to directly transform the thermal energy of exhaust gases into electrical energy. Due to their operating principle, TEGs have several advantages, such as low noise levels, the absence of moving parts, modular capability, zero emissions, and low maintenance costs [46]. A representation of a TEG is shown in Figure 6.

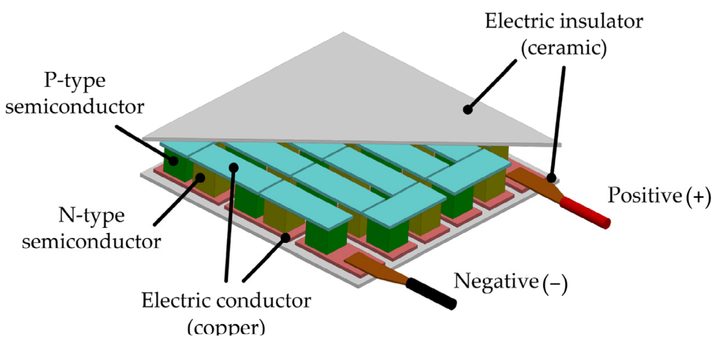

Figure 6. Schematic of the thermoelectric generator. Source: image created by the author.

Thermoelectric generators are made up of n-type and p-type semiconductors, which are connected thermally in parallel and electrically in series [47]. In the presence of a temperature gradient, a flow of electrons from the hot end to the cold end is produced, generating an electrostatic potential [48]. TEGs are recommended due to their light weight, lack of vibration, and high reliability.

4.2. Hydrogen Fuel

The available research available indicates that hydrogen is one of the most sustainable fuels. Hydrogen is characterized by being the cleanest fuel and with a higher energy content compared to gasoline or diesel. Additionally, the products of hydrogen combustion are free of contaminants [49]. Compared to traditional energy sources, hydrogen is considered a green energy source with a low carbon footprint and minimal greenhouse gas emissions. All of the above makes hydrogen a fuel that can meet humanity's future energy demands [50]. Figure 7 summarizes the benefits of hydrogen as an energy source.

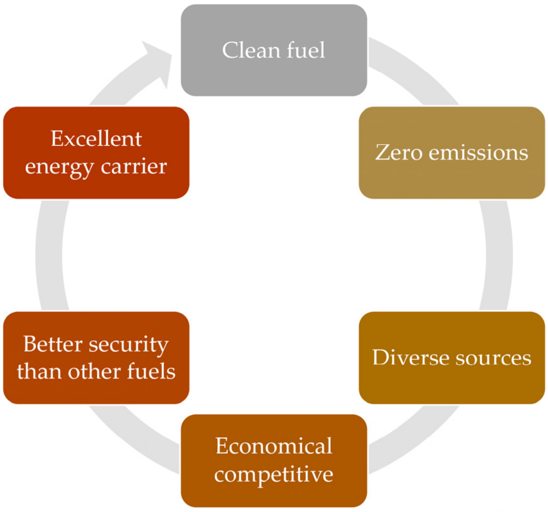

Figure 7. Advantages of hydrogen as a fuel. Source: image created by the author.

4.2.1. Hydrogen Production Routes

Figure 8 shows the main methods used for the production of hydrogen.

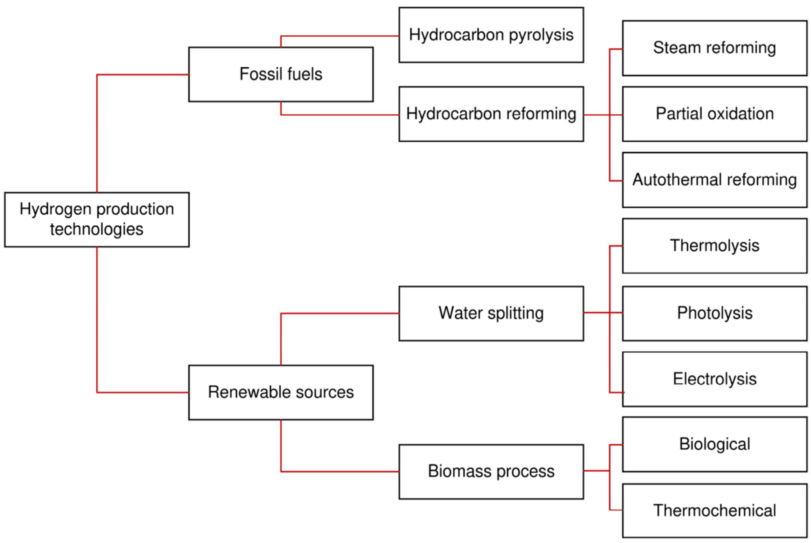

Figure 8. Hydrogen production routes. Source: created by the author.

Figure 8 shows that two types of technologies can produce hydrogen: renewable and non-renewable [51]. In the case of renewable technologies, hydrogen is obtained from the use of biomass as a raw material and the chemical division processes of water. For non-renewable technologies, hydrogen is produced from fossil fuels and processes such as pyrolysis and hydrocarbon reforming.

4.2.2. Hydrogen Production Methods

Depending on the method used for hydrogen production, it is possible to carry out a classification based on color codes that present the environmental impact of the technology. A summary of this classification is shown in Table 1.

Table 1. Environmental impact of hydrogen production methods. Source: created by the author based on data from [52].

Technology	Terminology	Environmental impact	CO_2 Emissions
Steam reforming	Grey H_2	Hight	Hight
Gasification	Blue H_2	Medium	Medium
Electrolysis	Green H_2	Low	Low

Steam Reforming

Steam reforming of natural gas using a chemical loop is an attractive way to produce hydrogen gas. This process consists of the partial oxidation of methane and the division of the steam into two stages, as shown in Figure 9.

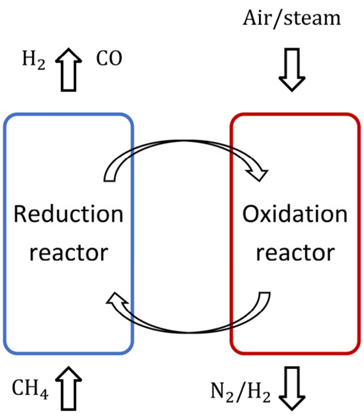

Figure 9. Methane reforming for hydrogen production. Source: created by the author.

In the first stage, methane is partially oxidized to generate a synthesis gas using oxygen molecules from a redox catalyst (oxygen carrier). During the second stage, the reduced catalyst is further oxidized by steam. On the other hand, the steam is divided for hydrogen generation. Equations (R1)–(R3) show an example of the hydrogen gas production process using steam and Fe_2O_3 as catalysts [53].

Reducer:

$$Fe_2O_3 + CH_4 \rightarrow FeO_x + CO_2 + H_2O, \text{ where } 0 < x < 1.5 \quad (R1)$$

Oxidizer:

$$FeO_x + H_2O \rightarrow FeO_y + H_2, \text{ where } x \leq y \leq 1.33 \quad (R2)$$

Combustor:

$$FeO_y + O_2(\text{Air}) \rightarrow Fe_2O_3, \text{ where } y \leq 1.5 \quad (R3)$$

Gasification

The gasification process involves converting carbon-based feedstock into synthetic gas using steam, oxygen, or air [54]. Gasification techniques use various types of raw materials and waste, such as coal, wood, plastic waste, and sawdust [55]. Among the products obtained from gasification are CO, CH_4, and H_2. The polluting material and particles that accompany the gas obtained must be purified with other substances. The main raw material used in the gasification process is coal.

For the production of hydrogen from coal gasification, coal is pulverized, dried, and ground in an air separation unit (ASU). Subsequently, the coal is sent to the gasifier to produce a synthesis gas. The CO gas produced reacts with water vapor to form H_2 and CO_2 in water gas shift (WGS) reactors. Finally, the hydrogen gas is purified by the pressure swing adsorption (PSA) system [56]. Figure 10 shows the schematic of the coal gasification-based hydrogen (CGH) process.

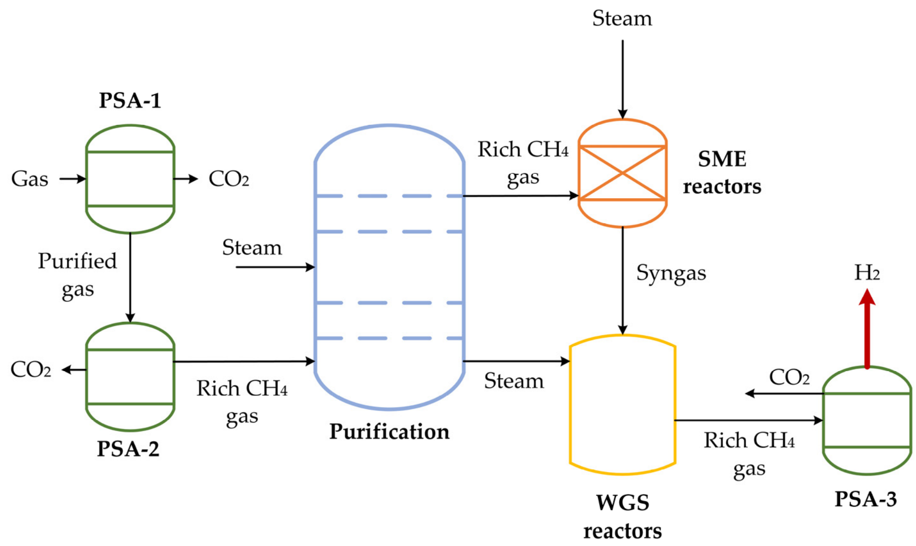

Figure 10. The scheme of the coal gasification-based hydrogen process. Source: image created by the author.

Electrolysis

The electrolysis of water allows the production of hydrogen using H_2O as the main raw material. Additionally, the only by-product they generate during the process is pure oxygen. During the electrolysis process, water (reactant) molecules dissociate into hydrogen (H_2) and oxygen (O_2) when exposed to an electrical current. The reaction of the electrolysis process of water is shown in the following equations.

Anode:

$$H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- \quad \text{(R4)}$$

Cathode:

$$2H^+ + 2e^- \rightarrow H_2 \quad \text{(R5)}$$

Overall cell:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad \text{(R6)}$$

Water electrolysis can be classified according to the type of ionic agent, electrolyte, and operating conditions. However, the main processes are alkaline water electrolysis (AWE), microbial electrolysis cells (MEC), solid oxide electrolysis (SOE), and PEM water electrolysis [57]. A schematic of the PEM water electrolysis is shown in Figure 11.

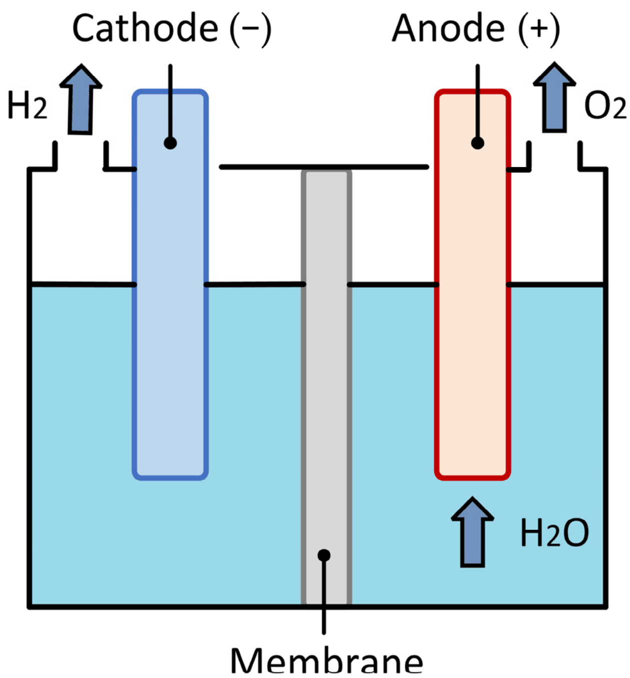

Figure 11. PEM water electrolysis. Source: created by the author.

In general, indirect water splitting methods for hydrogen production, such as electrolysis, prove to be a sustainable method for hydrogen generation due to the minimal pollution they cause and the considerably high efficiency of the chemical process [58].

5. Analysis and Results of Waste Heat Recovery Technologies

Tables 2 and 3 show the advantages, disadvantages, and impacts of the different waste heat recovery technologies applied in internal combustion engines.

Table 2. Comparison of recovery technologies applied in internal combustion engines. Source: created by the author based on data from [59].

Technology	Advantage	Disadvantages
Turbocharger	• Reduction in specific fuel consumption. • Low technical complexity. • Low volume. • Low cost.	• High exhaust back pressure. • Low efficiency with cheap equipment.
Organic Rankine Cycle	• Significant reduction in brake-specific fuel consumption. • No interaction with the engine.	• High technological complexity and cost. • High weight for automotive applications. • Toxicity (by working fluids).
Thermoelectric Generator	• Reduction in brake-specific fuel consumption. • Light-weight components. • No interaction with the engine. • Does not include moving parts.	• Low thermal efficiency. • Requires large heat transfer surfaces.

Table 3. Impacts of waste heat recovery technologies. Source: created by the author based on data from [60].

WHR Technologies	Refs.	Year	Type of Study	Result
Turbocharger	[61]	2023	Experimental	Specific fuel consumption can be reduced by 3.8% with optimal control of exhaust power distribution to the turbocharger.
	[62]	2021	Experimental	Energy and exergetic efficiencies with the turbocharger are increased by 1%.
	[63]	2019	Simulation	Turbocharged systems can achieve a 2.3% reduction in BSFC, and a maximum thermal efficiency of 10%, respectively.
Organic Rankine Cycle	[64]	2020	Experimental	The proposed system improves the thermal efficiency of the engine by 4.42%.
	[65]	2021	Simulation	The ORC system allows a reduction of 3.27% in the specific consumption of the engine, with an efficiency of 6.36%.
	[66]	2021	Review	Single-loop ORC systems can achieve a thermal efficiency of 25%.
Thermoelectric generator	[67]	2018	Experimental	The application of the TEG allows a decrease of 4% in fuel consumption.
	[68]	2019	Experimental	A maximum energy conversion efficiency of 2.83 % was achieved.
	[69]	2022	Review	The generators have numerous advantages: environmentally respectful, without moving parts, without work fluids, highly reliable, low maintenance, ability to operate in a wide range of temperature conditions, and direct energy conversion.

The described results show that applying waste heat recovery technologies based on organic Rankine cycles presents the highest thermal efficiency compared to turbochargers and thermoelectric generators. Additionally, the ORC allows a significant reduction in the engine's fuel consumption. Despite this, the high complexity of ORC systems causes a high economic cost that hinders their viability. Another main disadvantage of this type of technology is the use of highly polluting working fluids, which negatively impact the environment.

In the case of turbochargers, it is possible to demonstrate a significant percentage of savings in the fuel consumed by the engine. However, the engine's energy efficiency improvement is low compared to the other alternative technologies. This is due to the high pressure drop caused by the turbocharger on the engine's exhaust system.

Finally, thermoelectric generators have lower energy conversion efficiencies than ORC systems. Despite their relatively low efficiency, TEGs have several advantages that favor reductions in economic costs, such as their low need for maintenance and low technological complexity. Additionally, the TEGs do not directly interact with the engine, which facilitates their application without requiring considerable modifications. On the other hand, TEGs do not generate any negative effect on engine performance compared to other technologies. Another main advantage of TEGs is their zero emission of pollutants since they do not require the use of any type of auxiliary fluid due to their ability to transform energy directly. Therefore, TEGs are considered the technology with the greatest potential and feasibility for energy recovery from the exhaust gases of internal combustion engines.

Table 4 compares the advantages and disadvantages of the different hydrogen production methods.

Table 4. Comparison between hydrogen production technologies. Source: created by the author based on data from [70].

Technology	Advantage	Disadvantages	Efficiency	Cost
Steam Reforming	• Technology and infrastructure developed.	• CO and CO_2 emissions.	74–85%	∼ 2.27 USD/kg
Gasification	• Low economic cost and accessible raw material.	• Formation of tar. • Raw material dependent on seasonality.	30–40%	1.77 USD/kg–2.05 USD/kg
Electrolysis	• Established technology. • Zero emissions. • Use of renewable resources.	• Storage problem.	60–80%	∼ 10.30 USD/kg

The analysis of the results described in Table 4 shows that steam reforming and gasification are hydrogen-producing technologies with a low economic cost. However, both technologies lead to the formation and emissions of pollutants that affect the integrity of the environment. On the contrary, the electrolysis of water is free of polluting emissions. Additionally, electrolytic processes present a high efficiency of hydrogen production. Despite the benefits of water electrolysis for the production of hydrogen, its high economic cost makes its application difficult. This problem can be mitigated by taking advantage of renewable energy sources as a source of electrical energy for the electrolysis process, which allows sustainable hydrogen production at a reasonable economic cost.

6. Benefits of TEG and Hydrogen Gas in ICEs

Tables 5 and 6 show the results of studies on thermoelectric generators and hydrogen in internal combustion engines in recent years.

Table 5. Study of thermoelectric generators in internal combustion engines. Source: created by the author.

Refs.	Year	Type of Study	Methodology	Result
[71]	2019	Experimental	The performance behavior of a TEG system with different engine speeds and on the new European driving cycle was studied.	The power output of the TEG is proportional to the speed of the vehicle's engine. The TEGs maximum power output is approximately 214 W at 3750 rpm.
[72]	2019	Experimental	Installation of a thermoelectric generator in the exhaust system of a light transport vehicle.	Thermoelectric generators save up to 1.08% of fuel.
[73]	2020	Mathematical model	Development of a mathematical model based on the finite volume method for the analysis of a thermoelectric generator.	The thermoelectric conversion efficiency ranges from 1.41% to 4.12%.
[74]	2021	Experimental	The integration of a waste heat recovery module and a copper heat sink into the exhaust of a Honda GX120 engine was carried out.	The maximum power generated by TEG-27145 is 1.062 kW at a 3000-rpm engine.
[75]	2022	Simulation	Numerical simulation was used to evaluate geometric changes in the heat exchanger to increase electric power generation efficiency in vehicles.	The topological variation of the heat exchanger equipped with thermoelectric generators can lead to a recovery power of 700 W.
[76]	2022	Experimental	Experimental exhaust waste heat recovery tests were performed using a thermoelectric generator on a propane-fueled spark ignition engine.	At a 4500 rpm engine speed, the propane input TEG produced a maximum of 90.2 W of DC electrical power and a 3.02% energy conversion efficiency.
[77]	2020	Simulation	Finite element simulation techniques were used to investigate the application of TEG devices within ICEs.	Net power recovered through TEG reduces CO_2 emissions by 11–38 g CO_2/km.

Table 6. Study of the application of hydrogen in internal combustion engines. Source: created by the author.

Refs.	Year	Type of study	Methodology	Result
[78]	2020	Experimental	An engine was used at a constant load of 0.7 MPa and a rotation speed of 1500 rpm.	It was shown that the enrichment of CNG with hydrogen allows the improvement of the combustion process.
[79]	2020	Simulation	Using commercial software and a chemical kinetics solver, the behavior of an RCCI engine was simulated.	It was evidenced that the addition of hydrogen allows reaching an indicated gross efficiency of more than 50% and a significant reduction in emissions.
[80]	2020	Simulation	AVL Fire™ software was used to simulate the engine at different speeds, injection pressures, and air/fuel ratios.	Using HCNG with 30% hydrogen instead of pure diesel reduces specific fuel consumption by up to 14.13%.
[81]	2019	Experimental	A dual fuel (diesel–hydrogen) compression ignition engine with an EGR system was used. Engine load conditions were 25%, 50%, 75%, and 100%.	A 27.4%, 33.4%, 32.3%, and 20% reduction was observed in CO_2, CO, HC and PM emissions.
[82]	2021	Experimental	A low compression ratio turbocharged engine was employed. The tests were carried out at loads of 40 Nm, 60 Nm, 80 Nm, 100 Nm, and 120 Nm at a constant speed of 1750 rpm.	The pressure inside the cylinder and the rate of heat release increase with the addition of hydrogen flow.
[83]	2022	Review	A description of the experimental studies that have investigated the effects of hydrogen addition in four-stroke diesel engines was made.	Compared to other alternative fuels, hydrogen offers the significant benefits of zero carbon content, abundant quantities and production capacity using renewable energy sources.
[84]	2023	Simulation	A three-dimensional kinetic model of a Wankel engine fueled with different hydrogen fractions was developed.	The thermal efficiency of the brake with a hydrogen fraction of 6 % increased by 6.5%.
[85]	2022	Experimental	The influence of different percentages of hydrogen (0%, 6%, 12%, 18%, and 24%) at full load and a constant speed of 1500 rpm was studied.	Emission analysis indicates that CO_2, CO, and smoke are reduced by 3.61 %, 2.84 %, and 4.85 %, with an increase in the proportion of hydrogen.

The studies described in Table 5 make it possible to demonstrate the capacity of TEGs for the recovery of residual heat in internal combustion engines. The high flexibility of the TEG allows it to be adapted to particular needs depending on the characteristics of the heat source. Typically, exhaust systems have heat flows with a temperature between 100 °C–800 °C. The use of this significant amount of thermal energy makes it possible to promote sustainable development, achieving a reduction in the consumption of fossil fuels, a decrease in operating costs, and mitigation of polluting emissions. In general, TEGs are recovery technologies that, despite their low efficiency, can contribute to an increase in overall efficiency and reduce the environmental footprint caused by ICEs [86].

In the case of the results shown in Table 6, it is evident that the use of hydrogen as fuel in the ICEs makes it possible to reduce polluting emissions significantly. Since hydrogen does not contain carbon molecules, CO, CO_2, and HC emissions are considerably reduced. Additionally, hydrogen can be combined with other types of fossil fuels and does not require considerable modifications to be injected into the ICEs. On the other hand, hydrogen's high energy leads to improved engine performance parameters, such as combustion pressure, specific fuel consumption, and thermal efficiency.

The benefits in environmental protection and the economic sphere favor the sustainable development and competitiveness of the Colombian industrial sector. Due to the benefits of applying technologies such as thermoelectric generators and the addition of hydrogen in ICEs, their application in the industrial Colombian industry, especially in self-generation product processes, would allow considerable economic savings and a reduction in adverse effects on the environment.

Taking into consideration the results mentioned above (Tables 5 and 6), in this research, an analysis of the effects of the implementation of technologies, such as thermoelectric generators, and the use of hydrogen in the fulfillment of the following sustainable development goals (SDGs) was carried out:

SDG 7: Affordable and clean energy.
SDG 8: Decent work and economic growth.
SDG 9: Industry, innovation, and infrastructure.
SDG 11: Sustainable cities and communities.
SDG 12: Responsible consumption and production.
SDG 13: Climate action.

From the analysis of the specific targets for fulfilling the above SDGs, it is evident that implementing the strategies suggested in this research contributes significantly to achieving sustainable development in the Colombian self-generation industry. This is a consequence of better energy management, process optimization, emissions reduction, and implementation of cost-efficient technologies. Table 7 shows the specific SDG targets that can be addressed by implementing exhaust gas energy recovery through thermoelectric generators and using hydrogen as an auxiliary fuel in ICEs.

Table 7. Contribution of the TEG and hydrogen on sustainable development objectives in the self-generation industry in Colombia. Source: created by the author based on data from [87].

Sustainable Development Goal	Targets Addressed Directly	Contribution	Result
7 AFFORDABLE AND CLEAN ENERGY	• Increase substantially the share of renewable energy. • Double the global rate of improvement in energy efficiency. • Expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries.	Promote the use of renewable energy sources.	Improvement of the energy efficiency of the self-generation processes and increase in the participation of renewable energies.
8 DECENT WORK AND ECONOMIC GROWTH	• Achieve higher levels of economic productivity through diversification, technological upgrading, and innovation. • Improve progressively, global resource efficiency in consumption and production and endeavor to decouple economic growth from environmental degradation.	Modernization of technologies.	Increase in thermal performance in internal combustion engines through the combined use of residual energy recovery strategies and hydrogen production technologies.

Table 7. *Cont.*

Sustainable Development Goal	Targets Addressed Directly	Contribution	Result
	• Promote inclusive and sustainable industrialization. • Upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes.	Sustainable production processes.	Partial replacement of non-renewable fuels (natural gas) with green hydrogen without causing significant changes in the production process.
	• Reduce cities' adverse per capita environmental impact, including by paying special attention to air quality and municipal and other waste management.		
	• Achieve sustainable management and efficient use of natural resources. • Encourage companies, especially large and transnational companies, to adopt sustainable practices and integrate sustainability information into their reporting cycle.	Efficient use of energy resources.	Improvement in the process of converting the chemical energy of the fuel (natural gas) to useful mechanical power.
	• Integrate climate change measures into national policies, strategies, and planning. • Promote mechanisms for raising capacity for effective climate-change-related planning and management.	Incorporation of measures to reduce environmental impact.	Reduced consumption of carbon-based fuels.

The contributions described in Table 7 show that the use of thermoelectric generators and hydrogen gas in the Colombian industry supports the fulfillment of six of the 17 sustainable goals proposed by the UN. This is due to the positive impact on energy efficiency, reduction in fossil fuel consumption, and mitigation of pollutant emissions that come with the integration of recovery technologies such as thermoelectric generators and hydrogen gas as an auxiliary fuel.

In general, implementing TEGs and hydrogen gas injections allows for the compensation of thermal efficiency stagnation in internal combustion engines used for generation in the Colombian industrial sector, without requiring a highly costly technological change.

Additionally, the greater integration of hydrogen in the industrial sector allows contributing to the roadmap in Colombia, which aims to reduce the country's emissions to comply with the 2015 Paris Agreement through the implementation of green hydrogen.

Figure 12 shows a summary of the positive impacts associated with environmental, social, and economic aspects due to the use of thermoelectric generators and hydrogen gas in the self-generating industrial sector in Colombia.

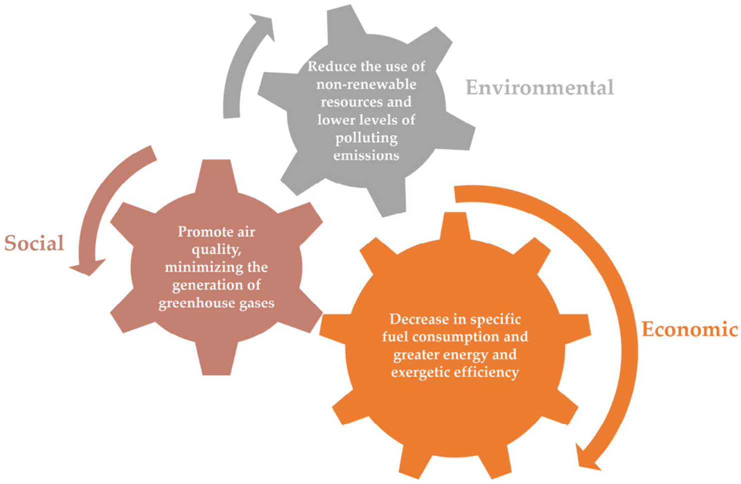

Figure 12. Impacts of TEG and hydrogen on the self-generation industry in Colombia. Source: created by the author.

From Figure 12 it is evident that the participation of technologies such as thermoelectric generators and hydrogen gas has a strong impact on environmental aspects due to the decrease in the use of non-renewable resources (fossil fuels–natural gas) and lower levels of polluting emissions as a result of the use of residual heat in engine exhaust systems.

On the other hand, hydrogen injection into the cylinder chamber leads to a more efficient combustion process, improving engine performance parameters, such as reducing specific fuel consumption and greater energy and exergetic efficiency. These benefits are reflected in a decrease in the operating costs of the industrial sector. All of the above contribute to an improvement in social well-being due to the reduction in the impact of the industrial sector on air quality in cities, and in general, due to a lower generation of greenhouse gases.

7. Conclusions

In this investigation, an analysis of the main technological strategies focused on the use of waste heat and hydrogen production to guarantee the progress and development of this Colombian industrial sector is carried out.

The analysis of the industrial sector in Colombia shows that internal combustion engines are the main technology used for self-generation in Colombia, with a share of 49%. The main fuel used is natural gas, with a percentage of 56%. This leads to high rates of residual heat flow in the industrial plant due to engine exhaust gases, which are generally released into the environment. This situation demonstrates the potential for energy recovery, which could be addressed to minimize the high percentage of energy loss in the industrial sector, which is approximately 36%.

The high-temperature conditions in the exhaust gases of ICEs allow waste heat recovery technologies to be used. Among the different existing technologies, thermoelectric generators stand out mainly due to their low complexity and low interaction with the engine. This facilitates the implementation of this technology in the Colombian industrial sector because it does not require significant modifications. The use of TEGs can lead to a 4 % reduction in fuel consumption and an overall improvement in the energy efficiency of engines used in self-generation. This is a consequence of the high thermal energy of the exhaust gases in the ICE, which can reach temperatures of 300 °C.

Studies indicate that hydrogen has the potential to reduce CO_2, CO, HC, and particulate emissions by 30%. The partial addition of hydrogen in ICEs allows for significant reductions in pollutant emissions and improved performance parameters. However, the sustainability of hydrogen depends on its production process. Among the existing technologies, water electrolysis allows for the production of green hydrogen (zero carbon emissions) with a high-efficiency rate of approximately 60–80%. The high availability of solar energy in Colombia can be used in electrolysis processes, resulting in lower hydrogen production costs.

The integration of waste heat recovery technologies such as TEG and the use of hydrogen in the industrial sector helps to meet several of the sustainable development goals proposed by the UN. This implies a great contribution to reform Colombia's commitment to the reduction in emissions stipulated in the objectives of the Paris Agreement of 2015. Additionally, it accelerates the participation of renewable energy sources in the Colombian industrial sector.

In general, the application of thermoelectric generators and the use of hydrogen gas are viable strategies for the utilization of the waste heat present in the self-generating industrial sector and solar energy sources in Colombia. Implementing these strategies allows for improving the Colombian industrial sector's environmental, social, and economic aspects due to the reduction in emissions, greater competitiveness, and operational costs. This contributes to the sustainable and economic development of the self-generating of energy in the industrial sector of Colombia.

The proposed research highlights the benefits of implementing technologies such as thermoelectric generators and hydrogen gas as fuel in the self-generation industry in Colombia, which have not been considered for the improvement of the energy management of this industrial sector. In this way, it seeks to expand the strategies proposed by the Colombian government to reduce the significant energy losses the country experiences in its industrial sector.

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