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Research Article

Towards sustainable cogeneration in an oil refinery: A synergy between ISO 50001 and ISO 14001 management systems

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Abstract. The most implemented standards worldwide for Energy Management Systems (EnMS) and Environmental Management Systems (EMS), ISO 50001 and ISO 14001 respectively, maintain a close correspondence due to the Harmonized Structure (HS) recently established by the International Organization for Standardization (ISO). However, achieving greater energy efficiency does not always align adequately with environmental issues, which is most evident in fossil fuel-based industries. Therefore, this work aims to propose a synergy based on coupling divergences between these standards and use it to evaluate technological changes in the cogeneration plant of an oil refinery, for better energy performance, environmental sustainability and the transition to renewable energy. The results show that the changes in technology increases electric efficiency from 14% to 45% and the rate of atmospheric emissions per unit of energy generated decreases by 17% on average. However, as fuel consumption doubles, the total emission rises by about 100%. This conflict between energy and environmental performance leads to an analysis of sustainability principles to better understand the relevance of the change in technology as an appropriate solution for the comprehensive improvement of the refinery's energy and environmental performance and the gradual transition to renewable energy. The findings of this work shed light on how to deal with the fossil fuel-based industry in the global landscape of urgent sustainable development.

Keywords: Tula refinery; energy and environmental performance; technological changes; sustainable resource management

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1. Introduction

There is a high and inherent interrelationship between energy and the environment. All types of energy are obtained from natural sources, and the use of energy always impacts the environment. This impact is not always negative. For instance, some processes associate mild impacts that the natural capacity of the environment can assimilate, so these processes are considered to satisfy principles of sustainable resource management (Gómez 2020). The importance to preserve the environment concerning energy issues just started to be discussed in literature since the earliest 1970. The Center for Energy and Environmental Studies at Princeton University faced a wave of energy and environmental problems that came to bear in the United States (Seltzer 2020). Not long after, in 1987 the United Nations introduced the concept of sustainable development as the "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (Dănescu *et al.* 2021). Nowadays, sustainable development aims to balance at least three main dimensions: economy, society and environment (Martins *et al.* 2024; Chaaben *et al.* 2024; Johri *et al.* 2024). As a line of action to address this issue, in 2015 the United Nations adopted the 2030 Agenda with 17 Sustainable Development Goals. Regarding energy, Goal 7 considers to "ensure access to affordable, reliable, sustainable and modern energy for all"; and concerning the environment, Goal 13 intends to "take urgent action to combat climate change and its impacts" (Mishra *et al.* 2024).

However, many industrial facilities worldwide, especially industries based on fossil fuels, are generating significant environmental impacts with serious consequences to the planet and all species that inhabit it (Filonchyk & Peterson 2023; Pata, Erdogan & Ozkan 2023). This is a major concern as fossil fuels remain the main source of energy in the world. (Hou *et al.* 2023). As reported at COP29, 2024 was another warmest year on record, maintaining the same annual sequence since 2014 (Jiang *et al.* 2025). It was estimated that global CO2 emissions from fossil fuels reached a record of 37.4 billion tons in 2024, 0.8% higher than 2023 (Friedlingstein *et al.* 2024). An oil refinery is a facility where several fossil fuels are produced, including the most used, gasoline and diesel, and at the same time, fossil fuels are used as the main energy source. As reviewed by Granados-Hernández *et al.* (2021), refineries use a significant part of the same fuels they produce to operate their plants and equipment, between 4% to 35% depending on operational factors. Also, they are one of the biggest energy-consuming industrial facilities (Rossi *et al.* 2020; Ulyev, Vasiliev, & Boldyryev 2018). Oil refineries pollute all parts of the environment: air, water and soil (Filonchyk & Peterson 2023). In Mexico, Pemex (Petróleos Mexicanos) is the state corporation that exploits, processes, and markets virtually all the nation's oil resources, following a current policy to achieve energy sovereignty. This organization includes a refining system consisting of seven refineries

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throughout the country: Minatitlán, Cadereyta, Madero, Salamanca, Salina Cruz, Tula (Granados-Hernández *et al.* 2021), and the new Dos Bocas, which is about to come into operation. Refineries help to satisfy society's energy demand but also affect air quality (Wu *et al.* 2022). They imply the emission of several atmospheric pollutants (Bodor *et al.* 2022). Some of the Pemex refineries are located near large cities. This is the case of the Tula refinery which is part of the Tula-Vito-Apaxco industrial corridor, 90 km north of the metropolitan area of Mexico City, one of the largest megalopolises in the world. Thus, the city's air quality is significantly impacted (Sosa *et al.* 2020), and affects the health of more than 20 million people. Natural gas is the fuel most used to produce heat and electricity in the Tula refinery. Natural gas combustion generates emissions of criteria pollutants such as CO, SO2, NO2, Pb and suspended particles PM10 and PM2.5. Organic and inorganic toxic pollutants, especially volatile organic compounds (VOCs) are also generated, as well as greenhouse gases such as CO2, CH4, and N2O (U.S. Environmental Protection Agency 2024). Toxic and criteria pollutants are considered to damage human, animal, and plant life, and greenhouse gases increase global warming (Filonchyk & Peterson 2023; Wu *et al.* 2022).

Several years ago, the Tula refinery implemented and certified an Environmental Management System (EMS) based on the ISO 14001 standard. The Tula refinery generates a large amount of waste, including solid waste, discharges, and atmospheric emissions, but one of the Significant Environmental Aspects (SEAs) on which great efforts are being made is atmospheric emissions from the burning of natural gas. As intended by ISO 14001, the organization must be committed to protecting the environment and responding to changing environmental conditions (ISO 2015), which involves progressive mitigation of the environmental impacts or if possible, avoiding them. Academic research and empirical evidence regarding ISO 14001 are extensive in literature and show that this is the most globally adopted standard for EMS (Bugdol, Goranczewski & Kadzielawski 2021; Hayat & Lohano 2025; Mosgaard *et al.* 2022; Muminović *et al.* 2023) bringing positive environmental impact on organizations performance (Chaves Almanza & Leon de los Santos 2024). The most common benefits observed on EMS are waste minimization (Mosgaard *et al.* 2022), savings in waste management costs, better corporate image and reduced consumption of energy and materials (Muminović *et al.* 2023), as well as the development of cleaner, safer and healthier products and workplaces (Chaves Almanza & Leon de los Santos 2024). Furthermore, the refinery has recently implemented and certified an Energy Management System (EnMS) based on the ISO 50001 standard, seeking greater energy efficiency (ISO 2018). As energy costs have risen due to increased global demand, this standard emerged to give organizations a better way to use energy (Esteves *et al.* 2025; Rampasso *et al.* 2019; Uriarte-Romero *et al.* 2017). After approximately 14 regional and local energy management standards (Laskurain, Heras-Saizarbitoria & Casadesús 2019), in 2011 the first version of ISO 50001 for the implementation of EnMS emerged, responding to the growing interest of using energy efficiently (Jovanović & Filipović 2016). Nowadays, ISO 50001 is the world's most implemented and certificated standard for EnMS (Laskurain, Heras-Saizarbitoria & Casadesús 2019; Uriarte-Romero *et al.* 2017; Jovanović & Filipović 2016).

Currently, the refinery's cogeneration plant does not provide the total energy requirement of the refinery; that is, the heat demand is almost met, but only about a third of the electricity requirement is provided (the rest is supplied by the public energy grid). Also, the plant consumes around 55% of the total energy used; therefore, the scope of the refinery's EnMS refers to this plant. As referred, within the cogeneration plant, the most Intensive Energy Use (IEU) is the combustion of natural gas for the operation of industrial boilers. Thus, through a synergy between its EnMS and EMS, the Tula refinery needs to assess technological changes in the cogeneration plant to increase energy generation and efficiency, and at the same time reduce the environmental impact of atmospheric emissions. As ISO 50001 was released recently, its integration with ISO 14001 is still few explored in the literature and in the practice of industrial, commercial and other organizations (Chaves Almanza & Leon de los Santos 2024). Furthermore, even in organizations with both EnMS and EMS implemented, increasing energy efficiency does not always align adequately with environmental improvements (Jeong & Lee 2022), especially in the fossil fuel-based industry. Therefore, the present work aims to establish a synergy between EnMS and EMS, from the novel approach of coupling divergences to comprehensively intend the improvement of energy and environmental performance and use it to evaluate technological changes in the refinery's cogeneration plant that promotes the transition to renewable energy. An analysis of sustainability principles is performed to confirm that transitional change increases sustainability.

2. Methodological and conceptual approaches

Figure 1 shows the methodological design for this research. Following this design, within a research methodology framework, firstly, a synergy analysis between the ISO 50001 and ISO 14001 standards is carried out from an unprecedented approach to identify relevant divergent aspects that are coupled taking advantage not only of the HS of all ISO management systems (ISO/IEC 2024), but going further, the natural symbiosis between energy and the environment; this is expanded upon in section 2.1. Secondly, a thermodynamic simulation model is programmed according to the proposed synergistic approach, to represent the performance of the current state of the cogeneration plant or baseline and two feasible scenarios due to technological changes that are to be introduced. This is expanded upon in section 2.2. Thirdly, a sustainability analysis through sustainable resource management principles is proposed to better understand the benefits of implementing the technological changes for the transition to renewable energy, which is expanded upon in section 2.3.

2.1. The synergy between ISO 50001 and ISO 14001

Based on the growing need organizations face today to integrate management systems from various disciplines, the International Organization for Standardization (ISO) has recently established a HS for all management systems standards, which involves identical clause (chapter) numbers, clause titles, text, and common terms and core definitions (ISO/IEC 2024). In this way, there is already a high correspondence between ISO 50001 and ISO 14001, especially in the latest versions, 2018 and 2015 respectively. However, implementing each standard separately does not guarantee sustainable energy development (Jeong & Lee 2022, Laskurain *et al.* 2015). Taking advantage of the close relationship between energy and environment, some studies have been carried out to integrate these standards based on their convergences (Cardenas *et al.* 2018, Uriarte-Romero *et al.* 2017, Chrysikopoulos & Chountalas 2018)). Therefore, this paper proposes a novel analysis of the divergence between

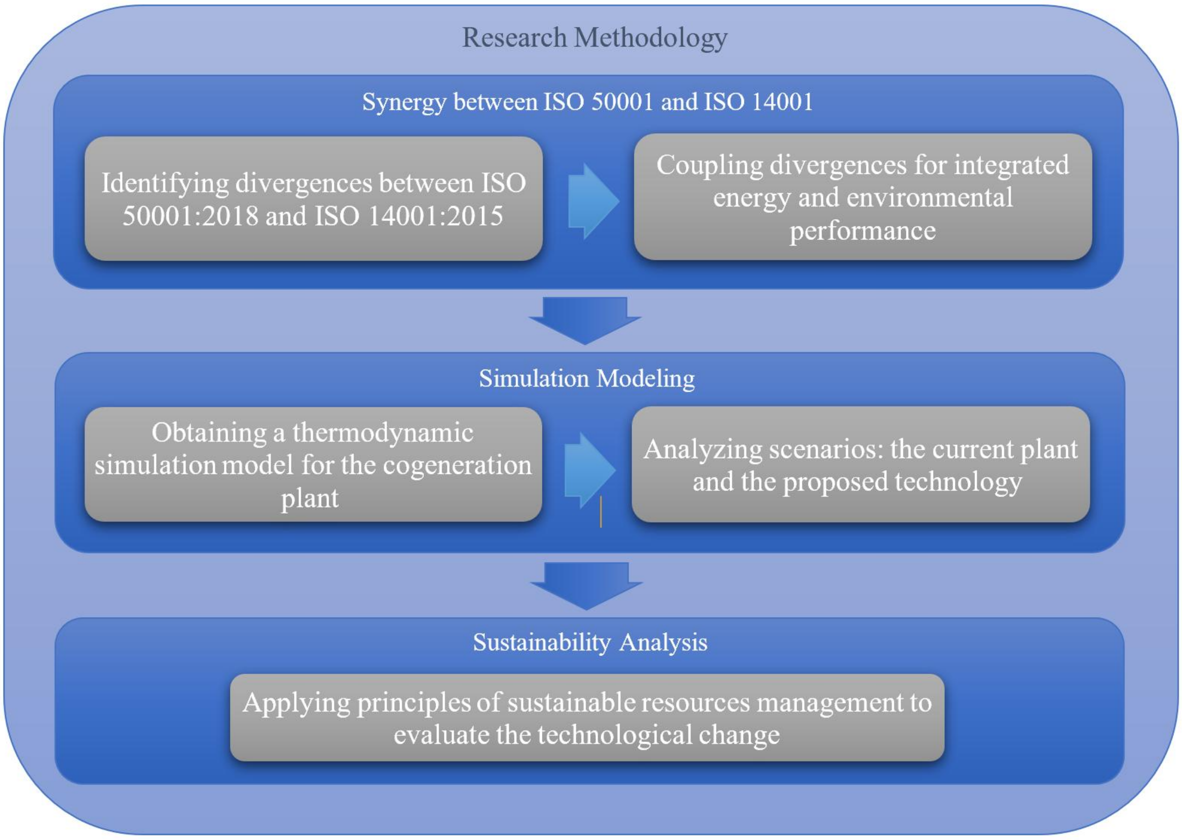

Fig 1. Methodological design

Table 1
Comparison of the structure of ISO 50001:2018 and ISO 14001:2015.

ISO 50001:2018 Structure			*Divergence with ISO 14001:2015*		
Clause ID	Title	#Sections	Match	Partial Match	No Match
4	Context of the organization	4	4	0	0
5	Leadership	3	3	0	0
6	Planning	6	1	1	4
7	Support	8	8	0	0
8	Operation	3	1	0	2
9	Performance evaluation	7	7	0	0
10	Improvement	2	2	0	0

these standards to establish a deeper synergy for driving a transition to renewable and clean energy. Based on the approach of Uriarte-Romero *et al.* (2017), a comparison of the sections in the clauses of the standards is conducted. Table 1 shows how many sections match, how many match partially, and how many do not match. "Planning" and "Operation" clauses are the only ones that have sections with divergences.

Then, the clause with the most divergences, "Planning", is analyzed in detail, so that strategies are proposed to couple these divergent aspects. All divergent aspects will be explored in future research. An overview of the "Planning" clause is shown in Table 2 as a comparison between both standards. Matching sections are in white, partially matching sections are in light gray, and unmatched sections are in dark gray

Therefore, relevant divergences between the two standards are observed in sections 6.3 to 6.6 of ISO 50001 that involve a quantitative approach not included in ISO 14001. This way, through an "Energy review", an organization is required to determine its energy consumption, especially identifying the IEUs. "Energy performance indicators" must be established to measure energy consumption, IEUs and other energy issues important to the organization. Then, from the data collected through indicators, an "Energy baseline" must be determined as a quantitative reference that provides a basis for comparison of energy performance, which can be obtained from a specified period and/or conditions, depending on each organization. For its part, from a qualitative approach, ISO 14001 requires an organization to identify its "Environmental aspects" to then establish and prioritize the SEAs that generate the critical environmental impacts.

Harmonizing these divergent aspects, a combined Energy and Environmental Review is proposed. It should reveal that most organizations experience a significant causality between IEUs and SEAs, especially industrial facilities with high use of fossil fuels. At the Tula refinery, an IEU is the use of natural gas for a set of boilers in the cogeneration plant. Consequently, large atmospheric emissions produced by the combustion of natural gas are identified as SEAs. Similarly, another coupling of

Table 2
Section divergence in the "Planning" clause of ISO 50001:2018 and ISO 14001:2015.

Clause		ISO 50001:2018		ISO 14001:2015	
		Section		Section	
6	Planning	6.1	Actions to address risks and opportunities	6.1	Actions to address risks and opportunities
				6.1.1	General
				6.1.2	Environmental aspects
				6.1.3	Compliance obligations
				6.1.4	Planning action
		6.2	Objectives, energy targets and planning to achieve them	6.2	Environmental objectives and planning to achieve them
				6.2.1	Environmental objectives
				6.2.2	Planning actions to achieve environmental objectives
		6.3	Energy review		
		6.4	Energy performance indicators		
		6.5	Energy baseline		
		6.6	Planning for collection of energy data		

Match Partial Match No Match

divergences lead to provide more accurate data, by using Energy and Environmental Cross Indicators that, together with conventional indicators, provide rich analysis. This should lead to establishing Cross Baselines that allow a broader view of comprehensive performance, affording better opportunities for sustainability.

In summary, the HS provides a common framework for clauses across all ISO management system standards. Based on this, a specific synergy between ISO 50001 and ISO 14001 is proposed due to the close relationship between energy and the environment, and is summarized in the following three points:

- *Energy-environmental review*. Causality between IEU and SEA. In the refinery's cogeneration plant, it is identified in the use of natural gas boilers, and therefore it is the process where technological changes are proposed to improve integrated energy-environmental performance as well as the transition towards sustainable cogeneration.
- *Energy-environmental indicators*. It corresponds to the set of cross and conventional indicators established to measure the integrated performance of the cogeneration plant, in the baseline and the technological changes scenarios.
- *Energy-environmental baseline*. It corresponds to the integrated energy-environmental performance in the current state of the cogeneration plant.

Under this proposed approach, simulation is used to predict and compare plant performance between the current and the feasible scenario, which is detailed below.

2.2. Simulation modeling

A simulation model is used to facilitate the analysis of the energy and environmental performance of a thermodynamic system as complex as the Tula refinery's cogeneration plant, which is much less expensive than if the analysis is carried out in the real facility. The model is used to represent three scenarios of the cogeneration plant: the current technological state, which will be referred to as the Baseline in accordance with the terminology of the standards; a technological change that optimizes fuel use, which will be referred to as the Optimized Fuel; and a technological change that optimizes fuel use and partially replaces it with a Renewable Energy (RE) source such as solar thermal energy, which will be referred to as the Transition to RE. The modeling of the cogeneration plant involves a system of non-linear thermodynamic equations and continuous entities, especially the fuel transformed into heat and electricity. Therefore, the plant must be represented by a nonlinear dynamic model that is best obtained through simulation. Based on Law (2022) before programming a simulation model, it is necessary to establish assumptions, a conceptual model, and performance measures. The simulation is then used to experiment with the different scenarios for specific predictions. Prior validation of the model is required to ensure the reliability of predictions, as discussed in section 3.1.

The main assumptions adopted for the simulation model have to do with the fact that the cogeneration plant is representative of the energy and environmental performance of the refinery; natural gas is sampled from all fossil fuels used as energy sources since it is widely used and considered IEU by the refinery; atmospheric emissions of CO2, CO, SO2, and NO are sampled from all environmental impacts since they are hardly controlled by Mexican regulations (NOM-085-Semarnat-2011) and are considered SEAs by the refinery; and energy demand for the refinery is considered unsatisfied, especially electricity, so higher electric energy generation is expected.

The model is programmed in Thermoflex ©, a general-purpose simulation software for modeling thermodynamic systems. This software has been widely used in the modeling of thermodynamic systems, several of these studies are referenced in section 3.1 on model validation. It uses a system of nonlinear equations solved by iterative methods to calculate energy and mass balances and applies the IAPWS-IF97 standard to calculate thermodynamic properties in critical water/steam/flow systems. Since the plant's workflow is superheated steam, the process follows a real steam power cycle or a Ranking cycle, which relates heat consumption to work production and is based on the transformation of water into steam and its subsequent expansion in a turbine. The thermal efficiency is given by the ratio of net work or the change in the kinetic energy and the heat input. Heat losses in the Rankine cycle are produced by the circulation of steam through the components of the facility and by irreversibility in the turbines and pumps that feed the boilers (Cengel & Boles 2011).

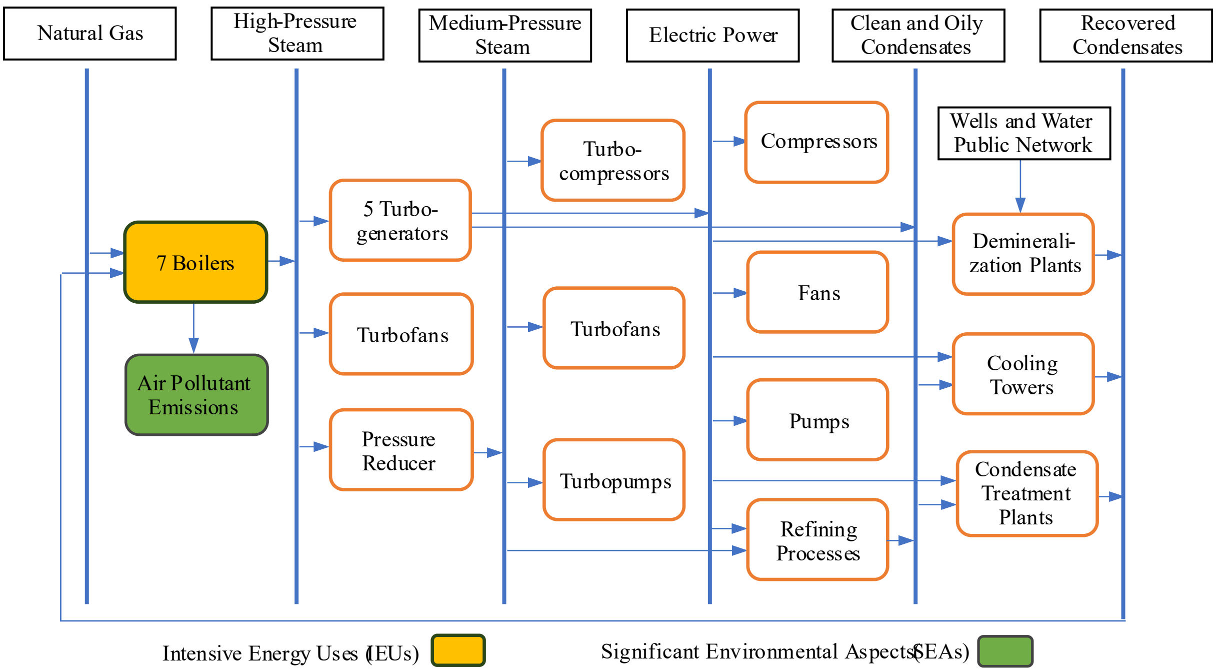

Fig 2. Scenario 1: Baseline of the Tula refinery cogeneration plant

2.2.1 Scenario 1: Baseline

Conceptual models for the three scenarios summarize Thermoflex's extensive model and technological changes. The baseline is drawn in Figure 2. According to it, the thermodynamic cycle begins with the operation of a set of seven boilers fueled by the combustion of natural gas, which the refinery considers an IEU, besides generating air pollutant emissions considered a SEA. The boilers generate high-pressure steam for the refining processes and cogeneration equipment such as turbofans, turbocompressors and turbopumps, some of which use medium-pressure steam obtained by a pressure reducer. But the high-pressure steam is especially used for a set of five turbogenerators, which provide electric power to refining processes and other cogeneration equipment, such as pumps, compressors and fans, as well as cooling towers and demineralization and condensate treatment plants. The latter are used to treat clean and oily condensates coming as a residue from turbogenerators and refining processes. The recovered condensates recirculate to the boilers, completing the thermodynamic cycle.

The model of Figure 2 summarizes the operation of three sections in the actual refinery configuration. The first section corresponds to the seven boilers, a fundamental part of the cogeneration plant. The other two sections represent the North and South areas, respectively, where the refining process plants are located, as well as several components of the cogeneration plant. The boilers are connected to a header that directs high-pressure steam to the North Area, where the turbogenerators are located. The boilers are also connected to another header that supplies them with recovered condensate for reuse and added demineralized water. The high-pressure header is set at a temperature of 482.2°C, a pressure of 60.12 bar, and an enthalpy of 3380 kJ/kg. Medium- and low-pressure steam headers are located in the North and South Areas and are set at 19.75 bar, 310°C, and an enthalpy of 3048 kJ/kg for the medium-pressure header, and saturated steam at 4.218 bar and an enthalpy of 2740.5 kJ/kg for the low-pressure header.

Recovery of clean condensate originates in the North and South Areas and is carried out at 45°C and 4.218 bar; similarly, oily condensates are recovered at the same pressure but at 65°C. The boilers are steam dome and induced draft. The natural gas feed has a lower calorific value of 40,156 kJ/kg at 25°C. The turbogenerators are simulated with an intermediate condensate extraction stage operating at 372.9°C and 19.75 bar (3,189 kJ/kg). The cogeneration plant has five supplementary boilers, three in the North Area and two in the South Area, which supply additional heat required by some system components. These are simulated as a heat exchanger that absorbs external heat and connects a water outlet when purging is required.

2.2.2 Scenario 2: Optimized Fuel

The first proposed technological change consists of replacing the boilers with a set of 4 natural gas turbines linked to a heat recovery system, as seen in Figure 3. This system consists of a superheater, two evaporators, and an economizer, which uses the turbine exhaust gases and, together with increased energy supplied by a duct burner, transfers heat to the returned condensates, then allowing for greater electricity generation. Thus, this technology demonstrates that the process is capable of using heat as an alternative energy source to the combustion of natural gas. The operation of natural gas turbines with heat recovery is founded in the Brayton cycle with regeneration (Cengel & Boles 2011), which is characterized by compressing air, mixing it with fuel, burning it and expanding the resulting gases in a turbine; the heat from the turbine exhaust gases is used to preheat the air, which is then used in a heat exchanger, in this case the superheater.

By joining a heat recovery system, heat losses are reduced and consequently, more energy is captured from the process (Li *et al.* 2018, El-Halwagi *et al.* 2009, Nguyen *et al.* 2010). The rest of the plant remains the same, with the configuration described in the Baseline scenario. In this case the set of turbines become

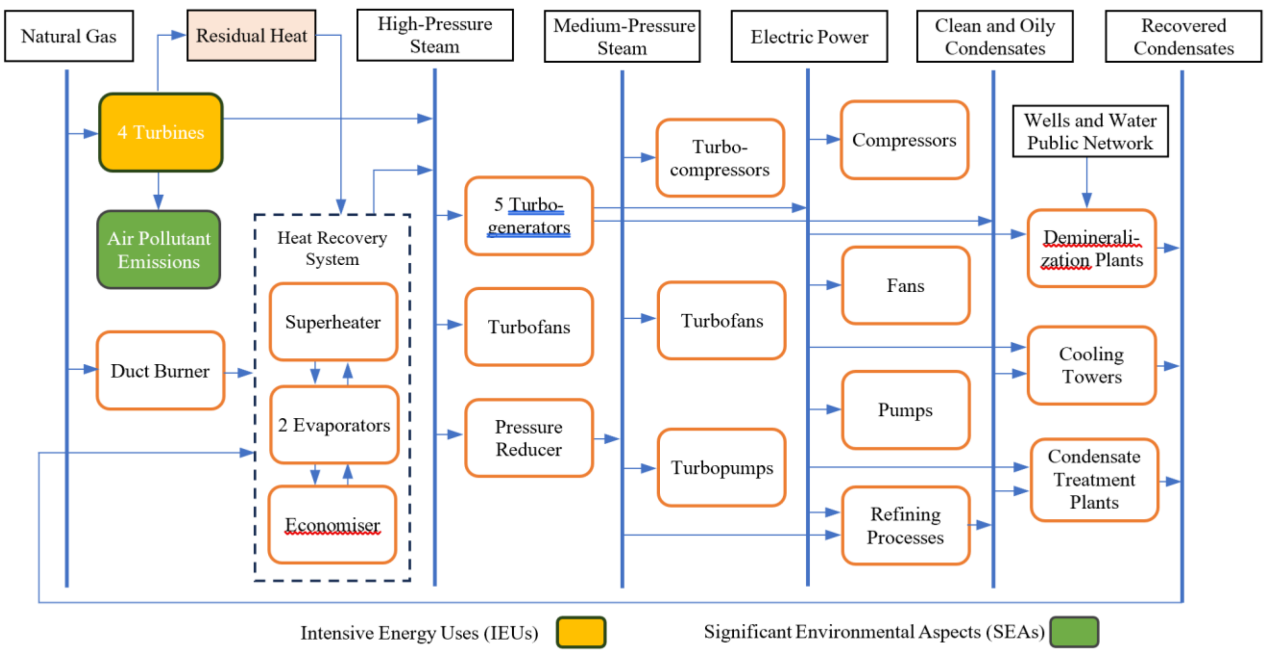

Fig 3. Scenario 2: Optimized fuel at the Tula refinery cogeneration plant

the IEU, generating an equal proportion of atmospheric emissions that continue to be the SEA.

2.2.3 Scenario 3: Transition to RE

Understanding from the technological change in the previous scenario that the cogeneration plant can use heat as an energy source, the third simulated scenario consists of introducing a renewable energy source into the heat recovery system. As shown in Figure 4, a solar field is connected that transforms solar energy into heat and is added to the heat recovered from the turbine exhaust gases.

As discussed in the following section, this technological change allows for a decrease in natural gas consumption. In this scenario, cogeneration uses two energy sources: fossil fuel and solar energy. Although natural gas consumption remains the largest source of energy, and therefore the IEU and the SEA, there is a partial shift toward renewable energy, thus marking the beginning of the energy transition.

2.2.4 Performance measures

The analysis of the energy and environmental performance of the plant through simulation involves defining performance measures that are used to compare all three scenarios, thus

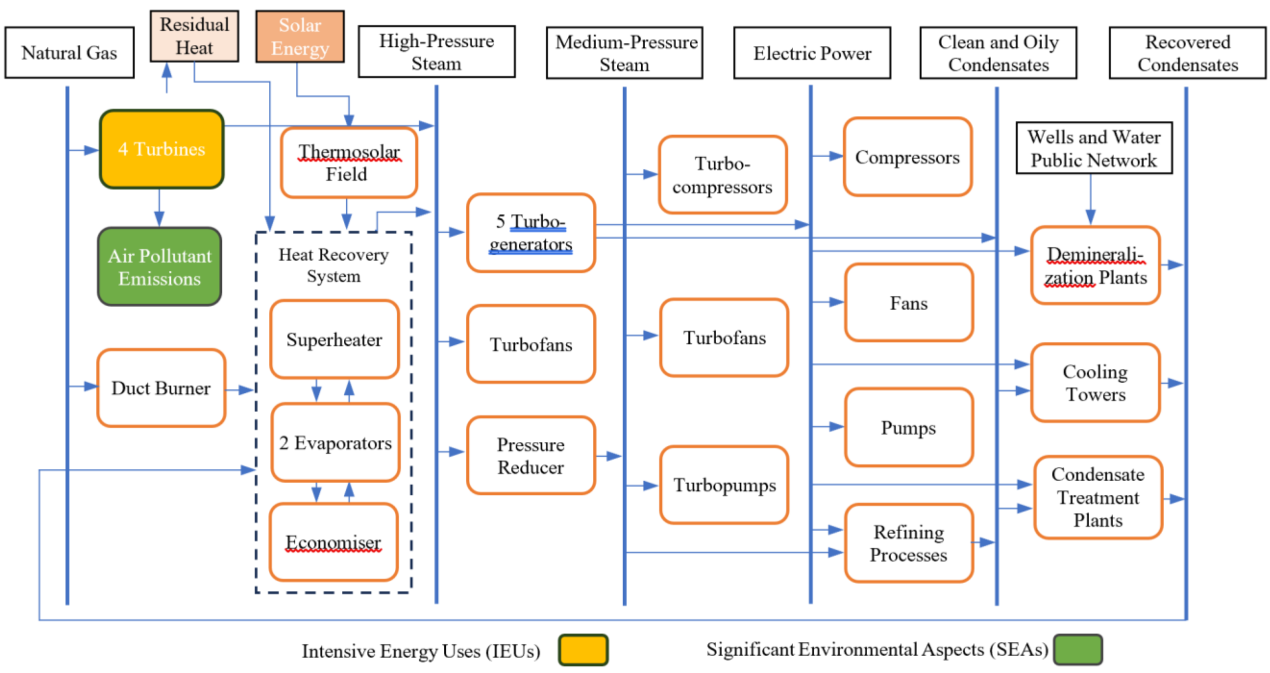

Fig 4. Scenario 3: Transition to RE at the Tula refinery cogeneration plant.

helping decision-making on the most sustainable alternative that increases energy efficiency and drives the energy transition. Following the proposed synergy between ISO 50001 and ISO 14001, the conventional and cross indicators established to analyze the integrated performance are described below:

Conventional indicators

- Energy and mass balances: It allows accounting for the flows of matter and energy in the thermodynamic transformation cycle in the cogeneration plant, evaluating the balance between inputs and outputs.
- Natural gas consumption: It is a measure of the fossil fuel energy used by the cogeneration plant, allowing the IEU to be quantified.
- Heat generation: It is the amount of heat energy generated by the plant and is expected to be maximized to meet the refinery's demand of 600 MWt.
- Power generation: It is the amount of electrical energy generated by the plant and is expected to be maximized to meet the refinery's demand of 500 MWe.
- Electric efficiency: It is the ratio of the useful electrical energy produced by the plant to the primary energy used from the combustion of natural gas to generate both electricity and heat. It is expected to increase with the use of released heat.
- Cogeneration (combined heat and power - CHP) efficiency: It measures how well the system converts primary energy from the combustion of natural gas into useful energy, that is, electrical energy and usable heat, both in the plant itself and in the refining processes. It is also expected to increase.
- Rate of energy consumption: It is the ratio between the energy consumed by the plant in kJ and the energy generated in terms of kWh of equivalent energy. It is expected to decrease.
- Total emissions of CO2, CO, SO2 and NO: It is the absolute measure of the emissions of atmospheric pollutants generated by the plant in a cycle, allowing the SEA to be quantified.

Cross indicators

- Emissions of CO2, CO, SO2 and NO per unit of energy generated: It is the proposed relative measure of atmospheric pollutant emissions per unit of energy generated, which most accurately shows the variation in the SEA.

Natural gas consumption is the measure chosen to validate the simulation model, comparing the values returned by the model with real values observed in the plant, as presented in section 3.1.

2.3. Principles of sustainable resource management

As discussed, especially in the fossil fuel-based industry, improving energy efficiency often entails greater environmental impact, even in cases where both EnMS and EMS are implemented, such as the Tula refinery. The proposed synergy between the standards aims to achieve a comprehensive improvement in the Tula refinery's energy and environmental performance. In this sense, the technological changes at the cogeneration plant promote the transition to renewable energy. Therefore, to confirm the benefits of this change, an analysis demonstrating the improvement in sustainability is proposed.

Based on the general principles of sustainability proposed by Herman Daly, Gómez (2020) refers to four specific principles of sustainable resource management that are relevant to evaluate the technological changes in the refinery's cogeneration plant. They are mentioned below and discussed in section 3.3.

- Principle of sustainable emission: the waste emission rate is equal to the natural assimilation capacity of the ecosystems where they are emitted.
- Principle of sustainable emptying: the rate of consumption of non-renewable resources is limited to the creation of renewable substitutes.
- Principle of sustainable selection of technologies: the appropriate technology for sustainable development is that which increases the productivity of resources, rather than increases the amount extracted from them.
- Principle of sustainable collection: the collection rate of renewable resources is equal to that of their regeneration.

3. Results and discussion

The results and discussion are presented according to the methodological and conceptual approaches, i.e., the proposed synergy between the standards described in section 2.1, the simulation methodology (section 2.2), and the sustainable resource management (section 2.3). First, the simulation model is validated to ensure it adequately represents the cogeneration plant. Second, the baseline is compared with the proposed technologies using conventional indicators, in the order mentioned in section 2.2. Third, the scenarios are compared using the cross energy and environmental indicators mentioned in section 2.2. Finally, the sustainability analysis is performed according to the principles established in section 2.3.

3.1. Model validation

In the validation of a simulation model, the most definitive test is determining that its output data closely resembles the output data observed in the real system. The model is considered valid if the two sets of data are closely similar. The accuracy of the model depends on its required use; therefore, there is no completely definitive approach for its validation (Law 2022). In the simulation model of the refinery's cogeneration plant, the output data used to validate the model is the natural gas consumed by the set of seven boilers. Thus, Figure 5 displays on the left a spider chart comparing the real and simulated t/h of natural gas consumption. Except for boiler CB5, the values returned by the model are lower than the real values. In any case, simulated and real values are close.

For a more accurate perception of the proximity of data, to the right of Figure 5, the percentage difference for each boiler is shown, where the smallest is 6.8% for boiler CB1 and the largest is 14.2% for boiler CB4. The median of these differences is 7.8%, an appropriate margin of error considering an acceptable range of 4% to 8% (Walpole, Myers & Myers 2012). Moreover, the correlation coefficient between real and simulated data is 0.6408, which is a strong correlation according to Cohen, cited by Lalinde *et al.* (2018). Therefore, the model is considered an adequate representation of the cogeneration plant.

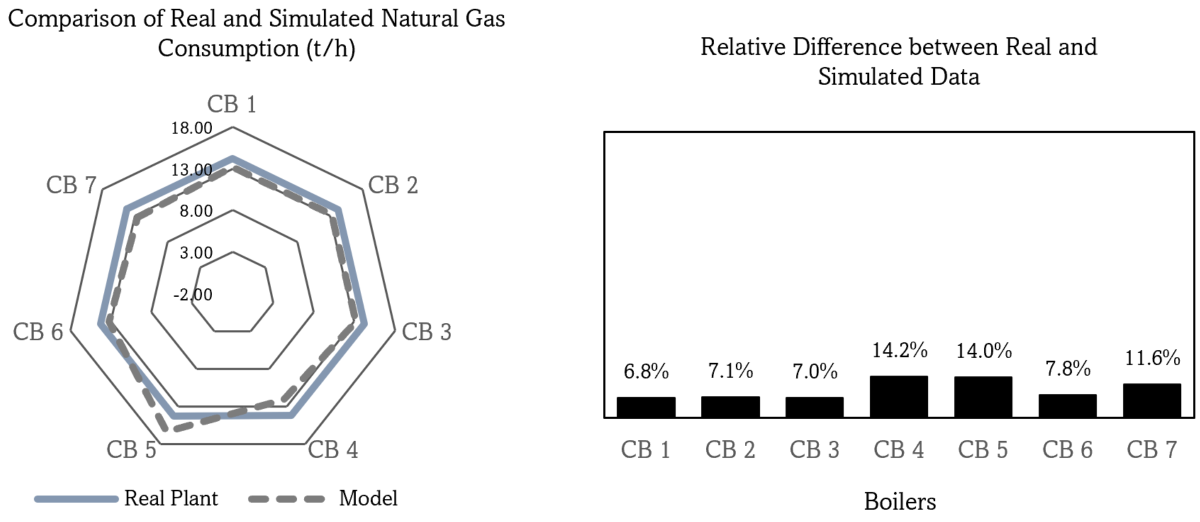

Fig 5. Plots of natural gas consumption contrast for the model validation.

Model validation is also confirmed by achieving zero error in the energy and mass balances, as presented in section 3.2.1. Otherwise, the simulation model would not be able to run. Additionally, Thermoflex software has great credibility as it has been widely used in the simulation of thermodynamic processes and systems. As in the research by Valdés & Leon (2019), this program has been mainly used in cogeneration processes in industry. Thermoflex simulation software has been used to assess the performance of the integrated solar gas turbine cogeneration with three different concentrating solar power technologies (Mokheimer *et al.* 2017). The work of Barigozzi *et al.* (2014) shows how the net power output can be maximized by properly regulating the combined wet and dry units of the combined cooling system, by using a detailed model of the steam cycle performed in Thermoflex. Also, for improving power generation on offshore oil and gas installations, four models of different power cycles were investigated, compared and evaluated using Thermoflow software package, including Thermoflex (Bimüller & Nord 2015). Frunzulica *et al.* (2014) develop the simulation of the cogeneration process applied to a residential building using the Thermoflex 25 © software from Thermoflow ©.

Table 3
Energy and mass balances.

Component	Baseline				Optimized Fuel				Transition to RE			
	Energy Balance (kW)		Mass Balance (t/h)		Energy Balance (kW)		Mass Balance (t/h)		Energy Balance (kW)		Mass Balance (t/h)	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Fuel sources	1,264,900		113		2,598,301		233		2,413,936		216	
Gas/Air sources	-0.004		1,762		-0.0126		6,541		-0.0126		6,541	
Pipes		13,394				20,286				20,293		
Process w/ return		584,223			-2,064	623,307	3		-2,269	625,177	3	
Turbogenerators		196,669				225,874				224,348		
Boilers	4,616	9,729		64								
Gas turbines						1,034,808				1,033,103		
Solar field									231,781			
Concrete stacks						458,392		6,774		456,239		6,757
Deaerator						3,641		71		7,366		144
Duct burner						247				61.25		
Economiser						2,907				244		
Evaporators						3,115				3,182		2
General pumps					2,828				6,601			
Superheater						2,264				2,265		
Vertical flow stacks		155,198		1,875		0		0		0		0
Water pumps	5,929				4,826				842			
Water treatment plants		-501,881		835		-526,930		887		-527,888		885
Water sources	-605,573		899		-658,925		955		-709,373		1,028	
Wet cooling towers		212,542				97,084			-5,583,250	-5,486,095		
TOTAL	**669,872**	**669,874**	**2,774**	**2,774**	**1,944,966**	**1,944,995**	**7,732**	**7,732**	**-3,641,732**	**-3,641,706**	**7,789**	**7,788**

3.2. Conventional indicators

The comprehensive energy and environmental performance of the plant is first analyzed through the energy and mass balances in the three scenarios and then complemented through the results of the other conventional indicators. In section 3.3, the analysis is extended through the proposed cross indicators.

3.2.1 Energy and mass balances

As mentioned, obtaining energy and mass balances confirms the correct functioning of the system. Table 3 details the energy and mass balances for the three scenarios analyzed. The error for both the energy and mass balance of the three scenarios is 0.000%, which confirms the reliability of the simulation model. Inflows and outflows are computed for all components involved in each case. With the proposed technologies, the energy and mass balances are obtained in quantities much greater than in the baseline. The proposed technologies increase energy consumption, but they allow for a proportionally greater increase in generation, as discussed with the results of the other measures.

In the baseline, the energy generated primarily from natural gas combustion is reflected in the energy inputs and outputs associated with the boilers. The release of air pollutants is observed in the energy and mass outputs of the vertical flow stacks. Furthermore, the return of condensate from refining processes involves an energy output with no recovery. In the optimized fuel scenario, the change from boilers to gas turbines is observed, with an energy output that also reflects this is the primary source of energy generation. The emission of gases into the atmosphere is now observed in the energy and mass outputs of concrete stacks. The substantial difference in this technology change is the recovery of residual heat, which is reflected in the energy input in the condensate return from the refining processes, with a negative sign indicating the direction of flow returning to the system. Similarly, the introduction of the heat recovery system is reflected in the energy output of its components: the deaerator, the economizer, the evaporators, the superheater, and even the duct burner. The transition to RE scenario is very similar to the previous scenario, but the key difference is the introduction of solar energy as a complementary source to recovered heat, which is reflected in the energy output of the solar field. This change implies a similar level of energy generation to the optimized fuel scenario, as seen in the energy outputs of turbines and turbogenerators, but a significant decrease in natural gas consumption, reflected in lower energy and mass inputs in the fuel sources.

3.2.2 Natural gas consumption and energy generation

Since the cogeneration plant is not supplying all of the energy demand needed by the refinery, fuel consumption is increasing in order to meet this requirement. Thus, the upper part of Figure 6 shows an increase in natural gas consumption

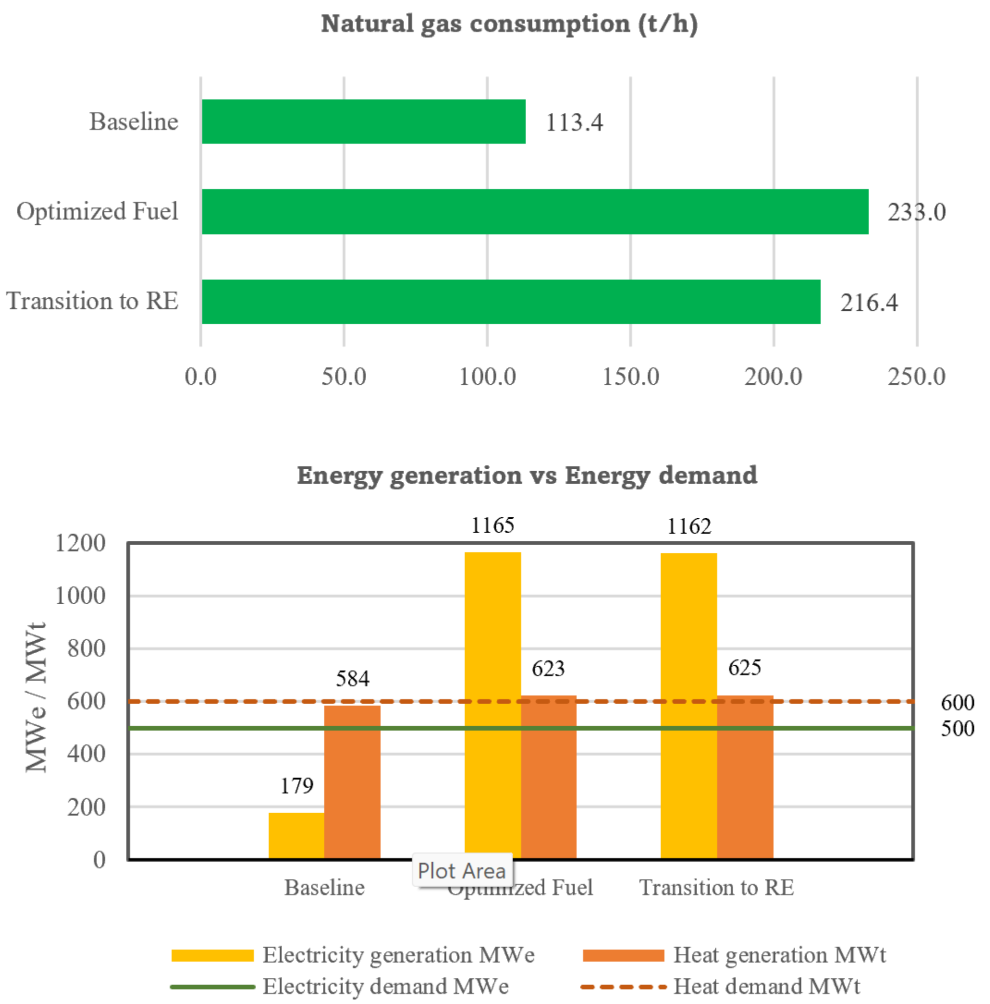

Fig 6. Comparison of fuel consumption and power generation between the scenarios

from 113 t/h in the baseline to 233 t/h in the optimized fuel scenario. This significant increase must be analyzed considering the other energy and environmental measures in order to observe the benefits of technological change. The transition to RE scenario has a decrease in natural gas consumption to 216 t/h, which corresponds to 7.3% compared to the previous scenario and is due to the partial replacement of fuel with solar energy.

At the bottom of Figure 6, the electrical and thermal generation of each scenario is compared with the refinery's electrical and thermal demands of 500 MWe and 600 MWt, respectively. As mentioned, the baseline is insufficient to meet the refinery's demands. Thermal generation reaches 97.3%, but critical electrical generation only reaches 35.8%, which is why the electricity deficit must be purchased from the public grid. In the scenario of optimized fuel, the cogeneration plant is able to meet the refinery's energy demands, with the added value that electricity generation exceeds demand by 133%, which can lead to an economic benefit from the sale of surplus energy to the public grid. The transition to RE scenario shows thermal and electricity generation values very similar to the optimized fuel scenario, but since it involves lower fuel consumption, it entails greater benefits in terms of efficiency and environmental impact, as discussed in the following sections. However, up to this point, meeting and even exceeding energy demand is a clear improvement in the energy performance of the cogeneration plant and the refinery in general, in compliance with the EnMS objective through ISO 50001.

3.2.3 Electric and cogeneration efficiency / Rate of energy consumption

Since efficiency can be interpreted as the maximization of resources used, the use of waste heat and the addition of a renewable heat source optimize fuel use, thus achieving greater efficiency (Chua & Foo 2021, Al-Owaidh *et al.* 2022, Mokheimer *et al.* 2017). The left of Figure 7 shows the electric and cogeneration efficiencies for the three scenarios. The electric efficiency rises from 15.31% in the baseline to 45.72% in the optimized fuel scenario, and a little decrease to 44.78% in the transition to RE scenario. Thus, the proposed technologies offer an increment of about 300% with respect to the baseline, which is largely associated with the implementation of the heat recovery system and the introduction of the solar source, as noted. Similarly, regarding the baseline the cogeneration efficiency, also known as combined heat and power (CHP) efficiency, has a substantial increase of 8.5% with the optimized fuel technology and 7.2% with the transition to RE technology. Cogeneration refers to the generation of two or more forms of energy, usually from one source (Chua & Foo 2021); in this case, power and heat generated from natural gas combustion. However, with the proposed hybrid technology, there is an additional source: the thermosolar energy, added to the use of residual heat from the combustion process. Thus, electrical efficiency grows much more than cogeneration efficiency because the residual heat and the heat from the solar source are used exclusively for power generation, while the high-pressure steam generated remains virtually constant (Mokheimer *et al.* 2017). The two proposed technologies scenarios have very similar efficiencies, but the transition to renewable energy scenario has lower fuel consumption, since part of it is replaced by solar energy. Therefore, the latter is the scenario that offers the best energy performance for the cogeneration plant and the refinery.

Compared to the baseline, the energy generation in the scenarios of proposed technologies is proportionally much larger in relation to the natural gas consumption. A clear insight into this issue is provided by the energy consumption rate, in fact, a cross indicator that only relates energy measurements. As shown on the right of Figure 7, around 25 MJ of energy supplied by the natural gas combustion is needed to generate 1 kWh of energy in the baseline, while only 8 MJ are needed to generate the same kWh with the proposed technologies. This confirms the improvement in energy efficiency with the proposed scenarios. Compared to the optimized fuel technology, the proposed hybrid technology has a small increase of 168 kJ consumed per kWh generated because, although it involves a lower fuel consumption of 185 MW, there is an additional 232 MW of energy consumed by the solar source, as shown in the energy balances. However, the energy consumption rates between these two scenarios are very

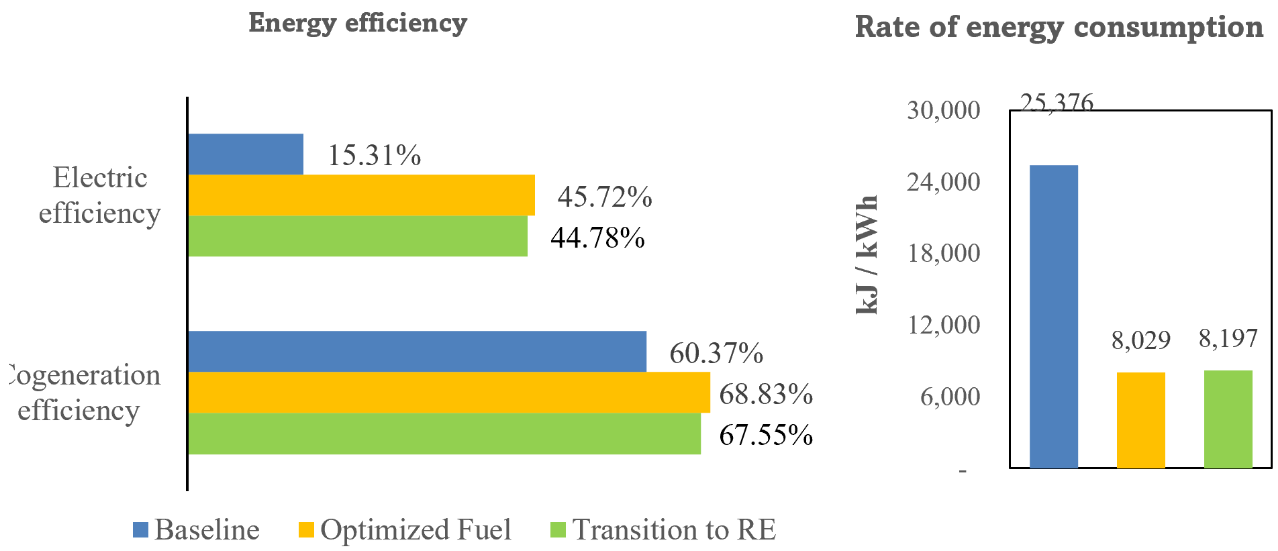

Fig 7. Comparison of efficiency and energy consumption rate between the scenarios.

Table 4
Emission factors of air pollutants (Leon, 1998).

Air pollutant		*Emission factor (t/GJ)*
Carbon dioxide	CO_2	6.715E-02
Carbon monoxide	CO	2.010E-06
Sulfur dioxide	SO_2	3.990E-05
Nitric oxide	NO	7.335E-05

similar, showing a substantial improvement of 68% less energy consumed per kWh generated compared to the baseline.

3.2.4 Total emissions of CO2, CO, SO2 and NO

Concerning environmental performance, emissions of air pollutants are estimated from natural gas consumption. For each polluting gas, an emission factor is multiplied by the amount of natural gas spent and for its lower calorific value of 40,156 kJ/kg, whereby the emission factor is the amount of pollutant emitted per unit of energy consumed in fuel combustion. Each fuel type has specific emission factors depending on its chemical composition. Natural gas even associates different emission factors for the same pollutant, since natural gas varies slightly in purity and composition from one source to another. For this reason, specific emission factors for the fuels most used in the industry of the Valley of Mexico are used (León, 1998). Table 4 presents the emission factor for each pollutant analyzed, in units of tonnes of pollutant per gigajoule of energy consumed.

Thus, the total emissions in tonnes per hour for the three scenarios are presented in Figure 8. On the left, the graph shows the emissions of CO_2 that are highlighted since they are significantly larger than the other pollutants, being the greenhouse gas that contributes the most to global warming (Filonchyk *et al.* 2024, Kanna *et al.* 2024, Bajoria *et al.* 2024). On a lower scale, the emissions of CO, SO_2 and NO are presented to the right of Figure 8, as criteria pollutants considered harmful to human health and dangerous to plant and animal life and thus the most regulated by Mexican legislation. As shown in these graphs, for the optimized fuel technology, the total emissions increase more than 100% with respect to the baseline, this is 322 t/h more CO_2, 0.01 t/h more CO, 0.19 t/h more SO_2 and 0.36 t/h more NO. This is due to the proportional increment in fuel consumption.

Regarding the optimized fuel technology, the transition to RE technology has a reduction in emissions of up to 7%. This is 44 t/h less CO2, with no significant decrease in CO, 0.02 t/h less SO2 and 0.05 t/h less NO. This is due to the lower fuel consumption that is replaced by solar energy, which is why this hybrid technology offers better environmental performance compared to the optimized fuel technology. Anyway, even with greater energy efficiency, the proposed technologies still represent a substantial environmental impact, as an inherent condition of the use of fossil fuels and still a major concern in environmental and public health matters (Umair *et al.* 2025, Lak *et al.* 2024). However, these conventional indicators are absolute and can give a distorted perception of overall performance, since energy generation increases in greater proportion to the increase in fuel consumption, whereby this work proposes to analyze the variation of emissions concerning energy generation, as a cross energy and environmental indicator in the synergy between EnMS and EMS.

3.3 Cross energy and environmental indicators

The level of emissions in relation to the energy generation is explored through the cross energy and environmental indicators thus making a more precise assessment of integrated energy and environmental performance, based on the synergy proposed. They are obtained by dividing the total emissions by the thermal energy plus the electrical energy generated, thus leading to compare the emissions of each pollutant per unit of energy generated, in units of tonnes of pollutant per gigawatt / hour of energy. These results comparing the three scenarios are presented in Figure 9.

In contrast to the total emissions, for the proposed technologies, the generation of one unit of energy implies fewer tonnes per hour of emissions. With the optimized fuel technology, the cross indicator decreases by 12% for CO_2, SO_2 and NO, and 17% for CO with respect to the baseline. This is 46 t/GWh less CO_2, 0.002 t/GWh less CO, 0.028 t/GWh less SO_2 and 0.05 t/GWh less NO. The use of waste heat obtained from exhausted steam allows for energy savings and a lower environmental impact (Pinto *et al.* 2022, Li *et al.* 2018, El-Halwagi *et al.* 2009, Nguyen *et al.* 2010). The proposed hybrid technology even offers a reduction in emissions per unit of energy generated, compared to the optimized fuel technology. This is 23 t/GWh less CO2, no significant decrease in CO, 0.014 t/GWh less SO2 and 0.027 t/GWh less NO. Compared to the baseline, this technology reduces emissions per unit of energy generated by 17% to 18%. This result demonstrates that the proposed technologies also improve environmental performance, especially the proposed hybrid technology. As noted, as long as fossil fuels are used, there will be polluting emissions, but the combination of natural gas combustion, residual heat recovery and solar energy allows for mitigation of

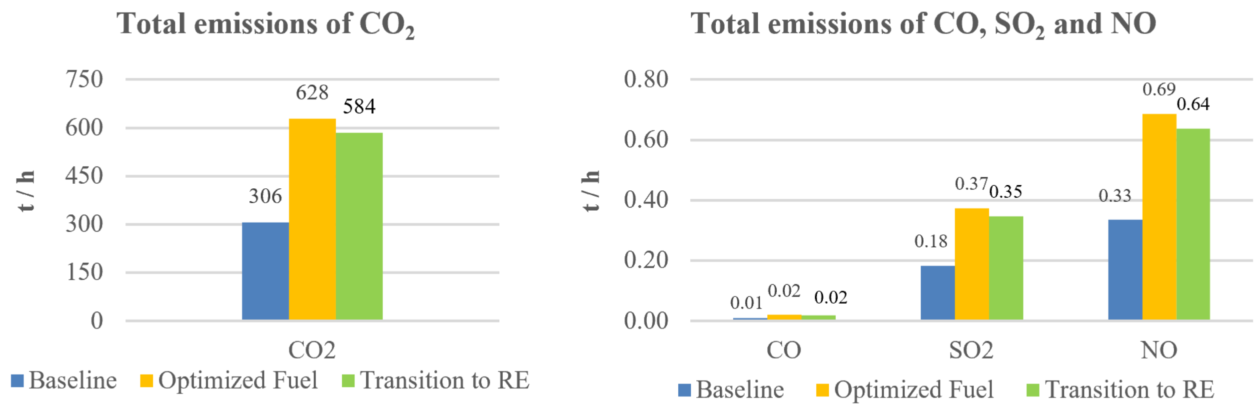

Fig 8. Comparison of total air emissions between the scenarios

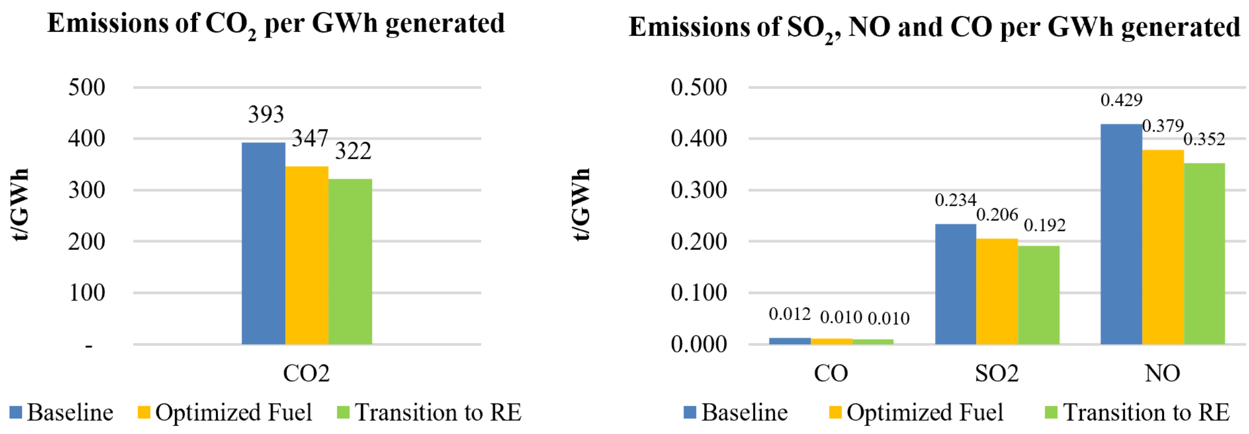

Fig 9. Comparison of cross energy and environmental indicators between the scenarios.

the environmental impact, as well as the transition to renewable energy. Therefore, the hybrid technology scenario is the alternative that offers the best integrated energy and environmental performance for the cogeneration plant, under the approach of the proposed synergy between EnMS and EMS.

3.4 Analysis of sustainable resource management

Although the volume of emissions generated still represents a significant environmental impact, the proposed hybrid technology with fossil and solar energy sources shows comprehensive improvements in the refinery's energy and environmental performance. Implementing this technological change is a sustainable initiative for the refinery, representing a valuable contribution as the first step in the transition to renewable energy. This is confirmed by analyzing the implications of the principles of sustainable resource management stated in section 2.3, as follows:

- Principle of sustainable emission: Since natural gas consumption increases to meet the refinery's energy demand and so do the total emissions, even with the proposed hybrid technology, the natural assimilation capacity in Tula ecosystems would be exceeded even further. Therefore, by continuing to use fossil fuels, this principle is not met, which is a cause of serious concern, not only for the impacts on the environment but also on public health, especially due to the proximity to Mexico City.
- Principle of sustainable emptying: For the proposed hybrid technology, the rate of natural gas consumption is lower than the baseline, since the heat released, added to the heat from the solar source, is used for energy generation. It means that a part of the non-renewable resource, natural gas, is being replaced by a renewable resource, heat from solar energy. Therefore, to start replacing fossil fuels with renewable energy is a major step forward in applying this principle. Renewable energy sources must be increasingly used, at least until the use of fossil fuels is limited to an assimilable rate.
- Principle of sustainable selection of technologies: According to the latter, the proposed hybrid technology clearly leads to increased resource productivity. That is, for each unit of energy generated, less equivalent energy is consumed, which is confirmed by the decrease in the rate of energy consumption from 25,376 in the baseline to 8,197 kJ/kWh. Therefore, the selection of this technology is sustainable and meets this principle.
- Principle of sustainable collection: Even with the technological change that introduces a renewable energy source, the plant still incurs a large use of non-renewable resources; however, the use of heat from solar energy as a renewable resource is now a relevant substitution. In the future, a greater substitution of fossil fuels with solar energy is expected, which would ensure the regeneration of used renewable resources because they come from an unlimited source. Therefore, this principle can be met thanks to the great opportunity to utilize renewable heat at the Tula refinery, as this area has significant solar energy potential.

The proposed hybrid technology offers improvements in three principles. It is not yet a completely sustainable solution but rather offers greater sustainability than the plant baseline. Therefore, this technological change is an appropriate transition solution towards the exclusive use of renewable energy. Based on this result, more efforts can be made in the future to promote the sustainability of the Tula refinery, such as greater use of thermosolar resources, adapting existing infrastructure for the refining of biofuels, and the implementation of waste treatment plants for a circular economy, which is an action already proposed by the country's new government.

3.5 Promoting renewable energy development

The Harmonized Structure represents a general framework for all ISO management system standards, as it unifies their structure into ten common clauses. In the specific case of EnMS and EMS, ISO 50001 and ISO 14001 respectively, there is a greater synergy given the close relationship between energy and environment, but it has been little explored. Therefore, from a divergence coupling approach, this work proposes to identify the causality between IEU, a key factor in EMS, and SEA, a key factor in EMS. Since these ISO standards apply to all types of organizations, this synergy is especially important in the fossil fuel-based industry, as the use of fossil energy has an inherent environmental impact.

This synergy leads to a comprehensive improvement in energy and environmental performance. In this way, an integrated baseline is established as a reference for improving performance through the use and monitoring of conventional and cross energy and environmental indicators. In the fossil fuel-based industry, this happens when there is a substitution by renewable energy sources. One way to achieve this goal at the Tula refinery is to introduce technological changes in the process where an IEU and a SEA converge: the use of natural gas boilers for cogeneration. The proposed hybrid technology replaces the boilers with natural gas turbines linked to a heat recovery system incorporating a thermosolar field. The fossil energy is not only optimized but also partially replaced by renewable energy such as solar energy. This change is a starting point in the transition toward the use of renewable energy as a sustainable source of cogeneration, which in the future can take advantage of the great solar energy potential existing in the area.

In this sense, the proposed synergy between the standards promotes renewable energy development, since it necessarily requires a transitional change in the use of fossil fuels towards renewable energy, while promoting the comprehensive improvement of energy and environmental performance.

4. Conclusions

Although ISO 50001-based EnMS and ISO 14001-based EMS have corresponding clauses thanks to the Harmonized Structure recently established for all ISO management systems standards, the synergy explored by coupling divergences goes beyond, taking advantage of the close relationship between energy and environment. This leads to a better understanding of the contradiction between energy efficiency and environmental performance in fossil fuel-based industries, where the necessity of gradually achieving the transition to clean and renewable energy is urgent, thus being a significant opportunity to accelerate sustainable development since these standards are the most implemented worldwide.

The Tula refinery case study is a relevant example of how to use this approach by implementing technological changes. The proposed synergy allows taking advantage of the causality between IEUs and SEAs, and using an enriched scheme of conventional and cross indicators for establishing combined baselines as a reference for the improvement of the comprehensive energy and environmental performance. Typically, in this type of industry, increased energy efficiency is achieved at the cost of greater environmental impact. The technological changes proposed under the synergetic approach improves both energy efficiency and environmental performance at the Tula refinery, essentially by partially replacing fossil energy with renewable energy from solar sources, thus initiating the energy transition. Therefore, this work sheds light on how to deal with fossil fuel-based industry, which is a big challenge in the landscape of sustainable global development.

The present research can also be used by standardization bodies and policymakers in promoting comprehensive regulations for energy development without compromising human well-being and the environment, thus encouraging the transition to renewable energy. Furthermore, future research could address synergies with other important standards for sustainable development, such as ISO 26000 for social responsibility, and expand experimentation to a set of organizations to observe best practices to accelerate the transition towards total sustainability.

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