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“INCORPORATION OF EXERGY IN THE NATIONAL ENERGY BALANCE”

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FIRMA

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Contents

Summary

Together with international efforts to mitigate the global climate impacts, Mexico has signed to accomplish the Paris Agreement. To achieve this purpose, it is essential to understand the energy sector's performance and its relationship with economic activities. This thesis proposes several new indicators to measure the performance of the energy sector: (1) Exergy intensity, (2) Exergy destruction per capita, (3) Exergy destruction per Gross Domestic Product (GDP), (4) Exergy efficiency, and (5) Entropy generated per GDP (6) Entropy generated per capita, (7) Internal exergy productivity.

The results showed that Mexico has a strong dependency on fossil fuels (92 % of the total primary exergy production), and exergy destruction (30 GJ/capita per year) implies a severe lack of sustainability in Mexico. However, Mexico's energy system has greater potential to become sustainable by incorporating renewables and changing the current trend in exergy supply.

Mexico experienced a drop in primary exergy production from 10,759 PJ in 2003 to 6,714 PJ in 2018. This drop in exergy production is mainly due to a reduction in oil production. Final exergy consumption increased from 4,218 PJ in 2003 to 5,092 PJ in 2018.

The average Mexican overall exergy efficiency is 63 % for the energy sector. The energy efficiency of the energy sector in Mexico was roughly 20% lower than energy efficiency, with substantially less improvement over the 15 years from 2013 to 2018. This difference arises from a strong dependency on fossil fuels and associated exergy destruction, which is not immediately apparent when taking only an energy perspective.

Exergy intensity shows the capacity of societies to transform exergy into economic output. The exergy intensity for Mexico was around 5 MJ/USD, very close to that of the UK's performance. The "internal exergy productivity" shows how much economic wealth was generated in the country by each unit of exergy extracted from the environment. In Mexico, a considerable increase is observed in internal exergy productivity, from 85 USD/GJ to 195 USD/GJ (from 2003 to 2018). This meant changes in the economic structure and public finances to generate financial wealth.

The economic value of exergy destruction could represent 2.9 % of the GDP in Mexico. A decreasing trend in the final exergy consumption is not necessarily reflected in lower exergy destruction. Those indicators provide information about Jevons' paradox. Furthermore, it points to substantial room for efficiency improvements in the energy sector, with important implications for greenhouse gas emissions. In addition, Exergy destruction and entropy increase indicators help the circular economy perspective to find the energy and raw material losses. This is one of the gaps in circular economy research nowadays.

By transforming the exergy perspective into public policies, Mexico would reduce the destruction of exergy, diminish its impact on climate change, and reach the national commitments under the Paris Agreement, because applying the exergy perspective in the national balances will allow policymakers to understand better opportunities to unlock new efficiencies and improve the sustainability of Mexico's energy system and those of other countries.

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Keywords

Exergy analysis, Energy quality, Exergy Factor, Energy sector analysis, Sustainability indicators.

Introduction

Climate change is among the most critical challenges facing the global community today. In 2015, countries around the world signed the Paris Agreement, committing themselves to limit global warming to well below 2 °C and to pursue efforts to limit warming to 1.5 °C. Mexico has unconditionally committed to a 25 % reduction in its greenhouse gas emissions by 2030 relative to its business as usual (BAU) projection. Based on Mexico's official BAU projection, this commitment implies a 40 % reduction in emissions per unit of GDP from 2013 to 2030 [1]. Achieving this and more ambitious goals present a significant challenge.

The latest IPCC report points out that major energy systems transitions are required to limit global warming [2]. The ability of Mexico or any country to reduce Greenhouse Gas (GHG) emissions – and its ability to meet broader social and economic goals – depends mainly on its ability to use scarce energy resources efficiently.

Countries rely heavily on national energy balances to understand and improve their use of energy resources. National energy balances present the origin, destination, and use of primary and secondary energy sources, for example, the amount of petroleum used, how oil is converted to electricity and liquid fuels, and where electricity and liquid fuels are used in buildings, industry, and transportation. By including energy losses, energy balances indicate the efficiency of the entire energy system and its parts. National energy balances have proven extraordinarily useful for analyzing energy systems' operations, designing public policies, and making energy-related decisions [3].

At the same time, national energy balances do not present a complete picture of the thermodynamic efficiency of an energy system. They are built on the first law of thermodynamics, which considers only energy conservation. They do not account for the quality of energy, nor do they consider thermodynamic considerations that determine the proportion of usable energy.

Energy accounting must turn to exergy analysis to gain a fuller picture of national energy systems. Exergy analysis is built on the first and second laws of thermodynamics. Incorporating energy quality provides a more holistic perspective on energy use and efficiency. The efficiency of an energy system is best understood as the proportion of the energy used, as opposed to the ratio of the total energy used. Given a particular amount of total energy, exergy is the amount of energy that may be transformed into physical work. Unlike energy, exergy is exempt from the law of conservation [4] – it can be created or destroyed [5]. Every process causes exergy destruction (entropy generation), representing a loss of energy quality [6]. Minimizing exergy destruction reduces the loss in the energy quality and increases energy efficiency.

Energy system researchers have long recognized the value of exergy analysis in understanding the characteristics of energy-related processes. According to Palazzo [7], it appears to be one of the perspectives for more efficient and rational use of energy resources and evaluating the impact on the environment and sustainability. *Most exergy analysis, however, focuses on equipment, devices, machinery, and power system performance*, for example, analyzing power plants [8], steam generators [9], heat pumps [10], solar-assisted power systems [11], buildings [12], smelting and pressing of metals [13], industrial processes [14]–[16], etc. *Exergy analysis and the concepts of destroyed exergy and exergy efficiency have been used for equipment and process performance* [17] *rather than the performance of an entire national energy system.*

Recognizing its value in the national context, however, several authors have explored the exergetic performance of national energy systems. This includes exergy analysis for countries and comparing system performance based on exergy and energy.

Losses in exergy could be considerably reduced in Brazil [18], Japan [19], Canada [20], Norway [21], the Netherlands [22], the UK [23], China [24], Portugal [25], and Italy [26]. Gong and Wall [27] conclude that the final useful efficiencies for most countries were about 20% when taking an exergetic perspective. Sejkora et al. [28] found Austria's exergy efficiency to be 34%. Mosquim et al. [29] found a 28% exergetic in the state of Sao Paulo in Brazil. Almasri et al. [30] conclude that there is room for improvement of about 12% in the residential sector in the Qassim region for exergy efficiency. Chen et al. [31] conclude that a net per-capita exergy resource input is the key to measuring the amount of available exergy used by society.

Other authors pointed out the possibility of analyzing energy, physical capital, labor, and environmental resources under the exergy measures [32]; these analyses use the Extended Exergy Analysis (EEA) [33]. Gong and Werner [34] pointed out that EEA is an excellent tool for reducing environmental impact. However, the Extended Exergy Analysis is beyond the scope of this thesis.

Previous researchers have performed indicators and research based on exergy analysis. Xie et al. [35] proposed three indexes, cost-based energy, cost-based exergy, and cost-based carbon, in the production phase in the building sector. In that way, they took into count all building materials. Biondi and Sciubba [32] used the extended exergy analysis in Italy; they call it the exergy footprint, which is sensitive to both environmental and economic factors, such as the financial capital or the final energy use mix (ratio of the exploitation of renewable and non-renewable sources). According to Rosen [36], the concepts encompassing exergy have a significant role in addressing climate change and increasing sustainable energy use.

Exergy methods represent an improvement in evaluating the primary resources' exploitation, transformation, and use [7]. Hernandez and Cullen [37] conclude that exergy efficiency is holistic, flexible, integrated, and transparent. However, the current situation in the exergy analysis at a macro level is that studies exhibit wide variation in assumptions and methods. Sousa et al. [38] highlighted and synthesized significant differences in the methodologies used to account for societal exergy consumption. Although nowadays, there are factors left out of the analyses when considering the exergy balances of a country [32].

Despite the demonstrations of national exergy analysis in these academic papers, *exergy analysis has not yet been taken up and used functionally for planning by national governments* nor by international organizations such as the International Energy Agency (IEA). There are at least three reasons for this. First, there is no standardized methodology for national exergy accounting that could be easily applied and replicated to facilitate everyday use and ensure consistency. Second, previous efforts have focused on these systems' technical and thermodynamic characteristics and have not tried to link these analyses to broader national goals, such as economic or climate goals. Third, the challenge is on the technical jargon that has not been able to spread the implications of the exergy method from the academy to other sectors, such as public policy. *It is required to continue making efforts in and outside the academy to migrate the exergy approach from engineering devices to countries and regions.*

This work seeks to contribute to filling these gaps. So, this thesis aims to develop new sustainability indicators based on exergy and create a straightforward method to incorporate those into the national energy accounting through the current energy balance. Therefore, this research aims to demonstrate that through new sustainability indicators, it would possibly evaluate the sustainability of the countries based on the exergy perspective.

The hypothesis raised in this research is: Exergy analyses are instruments that complement conventional energy analyses used to prepare national energy balances, so if the exergy analysis is incorporated, new information, new details of how energy is obtained, processed, transformed, and used, it can be added to the national energy balance information, contributing to a broadening of the information available for the country's energy system plans, research, and analysts, using new exergy indicators.

This work provides several contributions to the academy, the exergy community, and public policy. Chapter one is that it collated the methodology to calculate the specific exergy for fuels, which was the bases for estimating the "Energy grade function" or "Exergy factor," which results are shown in comparison against international data reported in the literature. It serves researchers who are interested in those data. The new approach to incorporating the exergy perspective into national accounting is a fresh perspective developed in Chapter 2; it brings an easy method to replicate worldwide. Moreover, to contribute to sustainability analysis, several indicators have been proposed. i.e., Exergy intensity, Exergy used and Exergy destruction per capita, Internal exergy productivity, Exergy destruction per GDP, Entropy generated per capita, and Entropy generated per GDP. In addition, Exergy destruction and entropy increase indicators measure the overall environmental impact, and they could help the circular economy perspective to find the energy and raw material losses. This is one of the gaps in circular economy research nowadays. Chapter 3 exemplified an exergy analysis by sectors and branches; its use will be illustrated in the beer industry. Chapter 4 Provides elements to integrate the exergy perspective into national and international policy.

The method proposed in this thesis can be replicated and applied to analyze other countries. International organizations can be urged to standardize this methodology. *They can be used to compare exergetic performance across countries. Based on this step-by-step methodology, energy-related indicators. It can therefore fill the same role as standard energy system indicators in informing policy and strategy.*

Chapter 1. Exergy, environment, and energy systems

1.1 Introduction

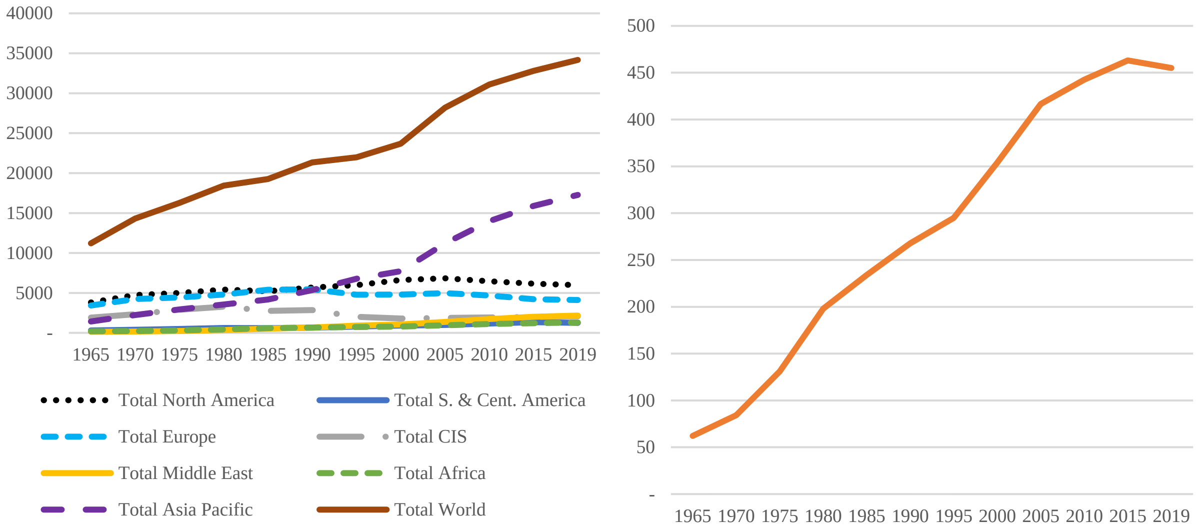
Climate change is a critical and interdependent issue facing the global community today and currently affects all regions of the world [39]. Changes in countries' energy mix and increases in energy efficiency are essential to achieve Greenhouse Gas (GHG) emissions and Net-Zero targets [2]. This chapter aims to overview the synergies between exergy, energy systems, and environmental impacts. Moreover, it is introduced the variables used in this research and their importance. The novelty of this chapter is that it collated the methodology to calculate the specific exergy for fuels, which was the bases for estimating the "Energy grade function" or "Exergy factor" for the main fuels used in Mexico. Finally, results in comparison against international data reported in the literature.

1.2. Energy and climate change

Human societies use natural resources to improve their living standards and provide for human necessities. Heating and lighting from wood were among the first uses of energy. As societies developed, they used a broader mix of energy sources like waterpower, wind, coal, oil, natural gas, sun, geothermal and nuclear energy.

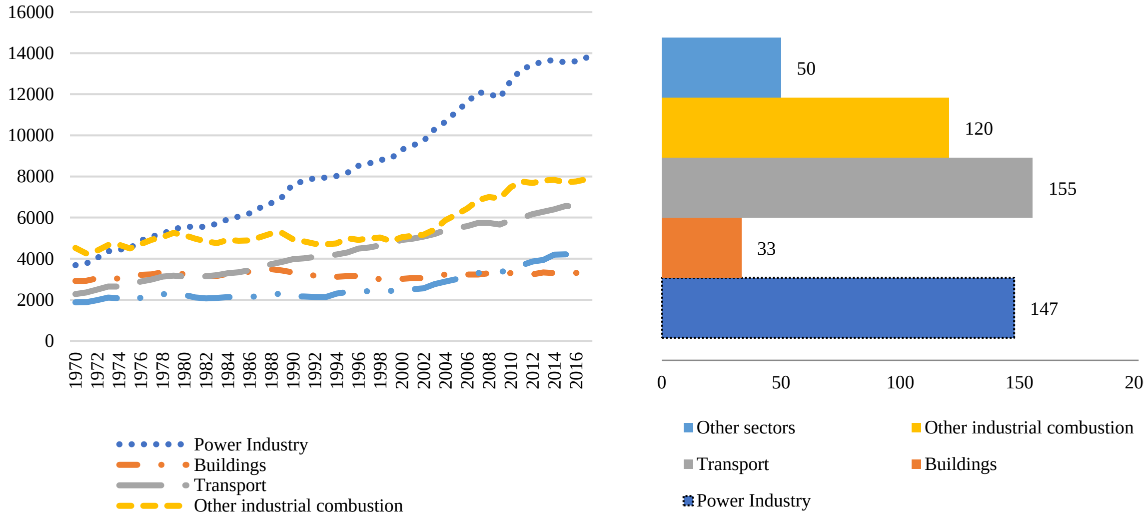
Energy has played a critical role in industrial and economic development. At the same time, however, inefficiencies, energy loss, and wasteful processes have led to critical environmental issues. As environmental issues have become more relevant, efforts to achieve sustainability have emerged and increased. The standard of living of contemporary societies is linked to high energy consumption, which is obtained mainly from non-renewable sources like fossil fuels - oil, coal, and natural gas. Its use is unsustainable over time because they are finite, exhaustible, and produces carbon dioxide (CO_2), one of the GHG that lead to global warming.

Climate change is among the most critical environmental consequences of energy use, but it is not the only one; the power industry, transport, and industry are the main fossil CO_2 emissions' responsible (Figure 1). According to the IPCC [39], human activities are causing climate change; there is a nearly linear relationship between cumulative CO_2 emissions and global warming. Mexico's CO_2 emissions have dropped during the last few years; however, the global CO_2 and GHG emissions continue to rise [2]. To limit global warming, strong, rapid, and sustained reductions in CO_2, methane, and other greenhouse gases are necessary [39].



(a) Carbon dioxide emission of all World by regions

(b) Carbon dioxide emission of Mexico



(c) Fossil CO_2 emissions of all World countries by sector

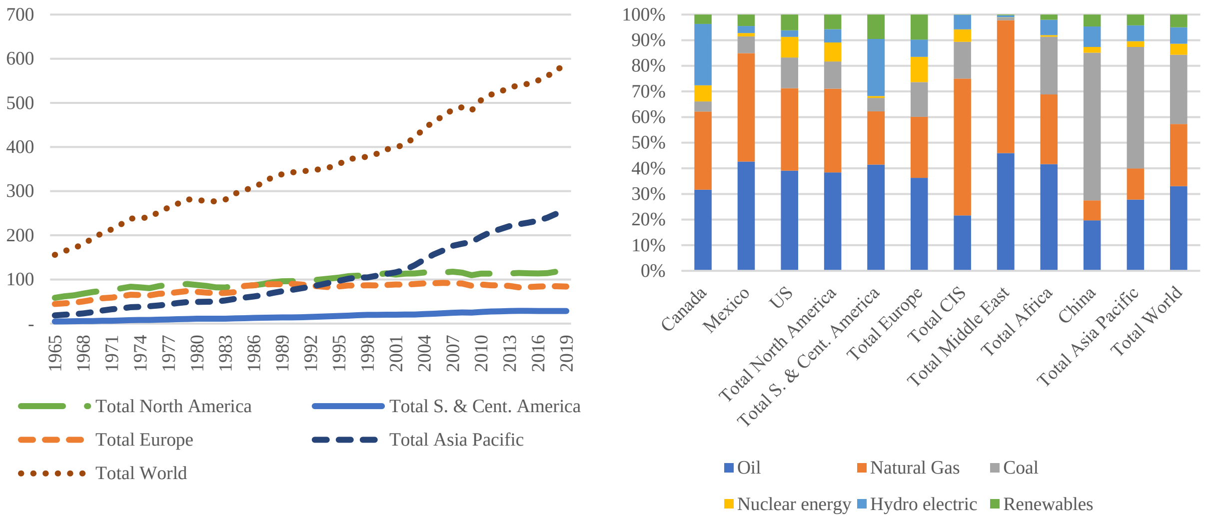
(d) Fossil CO_2 emissions of Mexico by sector, 2017

Figure 1. Carbon dioxide emissions [$MtCO_2$]. Source data: [40], [41].

The importance of natural resources as factors for economic development was evident during the last decades, for example, in 1972, the United Nations Conference on the Human Environment, held in Stockholm, or later in 1992 when it was recognized that the development of economics is linked to the environment as evidenced in the Rio conference.

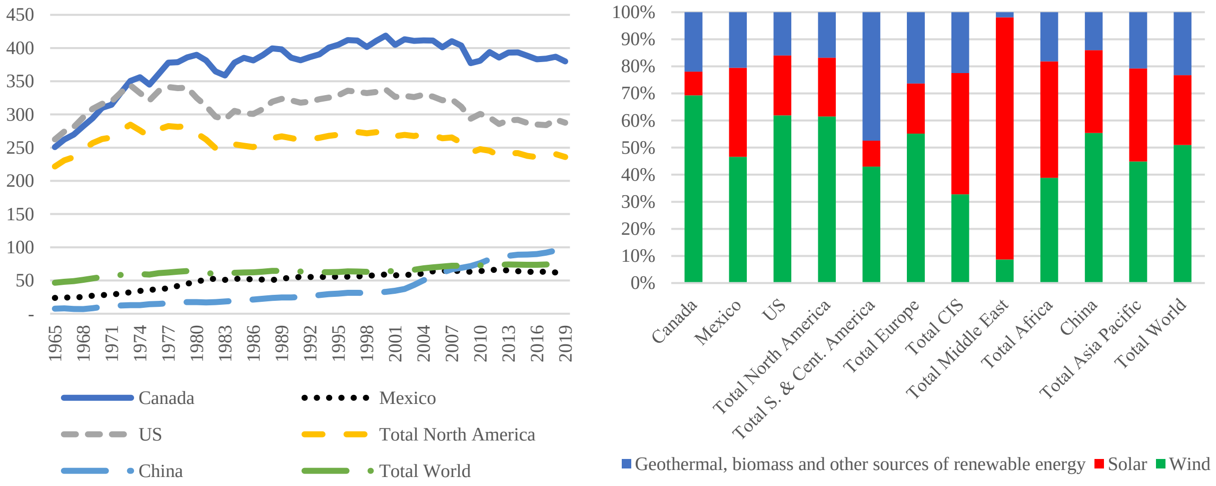
In 2015, countries around the world signed on to the Paris Agreement and committed to reduce their emissions to limit global warming to below 2 °C or to 1.5 °C. The active involvement of each country is needed to achieve this goal. Mexico signed the Paris Agreement in 2015 and committed to an unconditional reduction of 25 % of its (BAU) GHG and short-lived climate forcers (SLCF)s emissions for 2030. This commitment implies a reduction of 40 % of emissions intensity per unit of GDP from 2013 to 2030.

To limit global warming below 1.5 °C or 2 °C an energy transition from fossil fuels to renewables is needed [2]. Nevertheless, in 2019, the total primary energy consumption worldwide was 583.9 exajoules. In Latin America, the total energy consumption was 116.58 EJ; in Canada, 14.21 EJ; in Mexico, 7.72 EJ; and in the US, 94.65 EJ (Figure 2). US energy consumption represents 16 % of the world, and Mexico, Canada, and China represent 1.3 %, 2.4, and 24.3 %, respectively. Yet fossil fuels represent the main source of primary energy consumption in Mexico and worldwide. Its use is unsustainable over time, which is why Cooper et al. [42] conclude that we must: a) slow down its consumption, b) develop new sources of energy, c) efficiently use the exergy, and d) use technologies that demand less exergy consumption.



(a) Primary energy consumption [Exajoules]

(b) Primary energy consumption by fuel, 2020



(c) Primary energy consumption per capita. [Gigajoule per capita]

(d) Renewable energy generation by source, 2020

Figure 2. Energy consumption. Source data: [41].

1.3. The role of exergy in energy systems

The role of exergy in energy systems could have greater importance if exergy analyzes could be scaled from the traditional analyses – usually done to analyze devices and machines instead of the countries' energy sectors. Moreover, given the development of exergy analysis methodologies in the last thirty years, the national energy sector has not been able to break its limitations of use only in the academic sector and in applications for processes and machines.

Therefore, this work contributes to helping exergy analyses scale to macro and planning levels, and at the same time, they can be helpful beyond academic issues and could reach the role of analyzing national energy systems. It is a conclusion, desire, or feeling of the exergy community.

Mexico's energy sector contributes 40 – 45 % of its total CO_2-eq emissions [43]. An essential first step for any country to develop strategies to limit emissions is understanding its current activities, particularly those in the energy system. The standard approach to do this is through energy accounting. While energy accounting has proven useful, it does not provide information about energy quality. Energy quality is essential because it provides the information needed to obtain the maximum work per unit of input or to understand the quality of the energy across stages of a process.

Several activities involve extracting energy from the environment (low quality) and delivering it in a usable form (high quality) to the end-users. The energy supply system is the activities related to transforming energy from low quality to high quality and delivering it to end-users. According to Bhattacharyya [44], the supply involves indigenous production, imports or exports of fuel, and changes in stock levels. Transformation converts different forms of primary energies to secondary energies for ease of use by consumers. Conversion, transportation, and transmission of energy involve losses. The final users utilize various forms of energy to meet the needs of cooling, heating, lighting, motive power, etc. The current way to account for energy in this process is through national energy balances and energy indicators.

Energy indicators were first used to understand countries' economic use of energy resources, but they have increasingly been pushed into the environmental assessment service [2]. Energy indicators do not, however, provide a holistic view of energy use and efficiency. Current and future problems need fresh perspectives to evaluate environmental impacts and measure the success of economies and societies in addressing economic and sustainability issues. Exergy analysis provides one alternative perspective.

Energy consumption measures the quantity of energy used by a specific sector, economy, or country. It does not, however, consider the quality of energy. Exergy, in contrast, incorporates energy quality. Exergy measures the part of the energy that may be transformed into other forms without restrictions [45]. Electricity, for example, has 100 % exergy. This means that all the energy can be converted into useful work - electricity could deliver power that could be used with 100% theoretical efficiency and that could match any other fuel in creating high temperatures [46]. According to Serrenho [47], there are heat losses when converting kinetic energy to work, but they are unknown a priori, thus one decides to consider an efficiency of 1, which is the theoretical maximum given by the first law of thermodynamics, i.e., there is no theoretical thermodynamic result that sets a maximum conversion efficiency in this case. Therefore, Serrenho considers electricity as 'pure work.' In contrast, not all the energy from fossil fuels – coal, natural gas, and oil – can be transformed into useful work. Heat cannot be converted entirely to work. In this case, the maximum work extractable from a sub-system connected to a thermal reservoir at T_0 is the work obtained by an ideal Carnot engine [47].

There are three types of energy, and each corresponds to a different quality: (1) energy which has no limitation to transform itself into another form of energy – this kind of energy has 100 % quality because it has 100 % convertibility (e.g., electricity). (2) energy that has limitations to partially transform itself into other forms of energy – this kind of energy has between 0 % and 100 % quality because it has some physical restrictions to totally convert one kind of energy to another (e.g., heat); and (3) energy that is not transformable at all (e.g., thermal radiation from Earth [27]) – this kind of energy has 0% quality [48], [49].

Unlike energy, exergy can be created or destroyed. Eventually, systems tend to the thermodynamic equilibrium, reflecting the elimination of thermal gradients [50]. Exergy destruction (*Bd*) is that part of the available energy (exergy) that could be used for useful work but was not. According to Pal [6], it is calculated by: $\mathrm{Bd} = \mathrm{mT_0}(s_2 - \mathrm{s_1}) = \mathrm{mT_0 S_{gen}}$. In most processes, the exergy destroyed is lost as low-temperature heat. In some other cases, it is lost as chemically reactive materials. Ultimately, it is dissipated into the environment [50]. The exergy destruction results due to irreversibilities - Gouy-Stodola, theorem [51].

National energy and exergy accounting arises from applying the laws of thermodynamics to the performance of national energy systems. Energy accounting is based on the first law of thermodynamics, which states that mass and energy must be conserved [50]. The implication is that energy use can be tracked across a country. The first law of thermodynamics helps to identify primary energy sources used in the country, track the energy consumption across the sectors, understand how energy is transported, and identify energy losses.

By incorporating energy quality, exergy analysis provides a window not only into energy use but also the efficiency of that use. Exergy analysis makes it possible to determine the energy system's efficiency by considering quantity and quality. Evaluating exergy flows in countries and regions provides a more realistic measure of the use of energy resources, their economic contribution, and their environmental impacts. Most of the exergy analysis has been applied to industrial sectors or processes; however, it can be used to analyze larger systems like countries, regions, or economic sectors [52], [53]. An exergy approach was introduced in 1975 to analyze the US [54]. Several other countries have been analyzed using a modified version of this approach since then [18], [20], [24], [33], [47], [52], [53], [55]–[58].

Exergy provides a better understanding of the sustainable level of energy systems in the biophysical context [59], [60]. Exergy methods could improve environmental and sustainability analysis [61], increase efficiency, and decrease losses and ecological damage [62]. Entering exergy balance in national accounts has become critical [27] to develop a standard exergy efficiency and exergy auditing methodology and a universal language among practitioners [37].

1.4. Exergy for fuels

To incorporate exergy perspective into the national accounting, the specific exergy of a substance must be estimated for all energy carriers. The overall specific exergy of a substance is the sum of its physical and chemical-specific exergy [63]. Michalakakis et al. [64] state that the substance’s chemical exergy is the materials’ exergy content due to its chemical composition. The following assumptions were made to calculate the exergy for fuels (1) A 100% combustion reaction efficiency is assumed [65]. (2) Elevation does not affect the combustion process; therefore, the physical exergy equals zero. (3) Fuels are considered to burn at a fixed location; therefore, the kinetic exergy is zero. (4) It is assumed that fuels are not subjected to electrochemical reactions; therefore, the electric potential is zero.

According to Song et al. [66], a specific chemical exergy correlation for solid and liquid fuels [b] is represented in Eq. (1):

$$b = (363.439\, C) + (1075.633\, H^*) - (86.3088\, O) + (4.14\, N) + (190.798\, S^*) - 21.1\, (A^*) \quad \text{(Eq. 1)}$$

C, H, O, N, S**, and *A** are the chemical composition of the fuel. Table 1 shows the exergy calculation for diesel fuel in kJ per kg. Diesel composition were taken from [67], [68]. Equation 1 was used to perform all the exergy calculations for all solid and liquid fuels, and here Table 1 shows Diesel exergy calculation as an example of the exergy calculation of liquid fuel. To calculate exergy´s solid fuels, Equation 1 works as well.

Table 1. Diesel's chemical composition and its exergy calculation.

Diesel			
Component	% w	Constants	b [kJ/kg]
Carbon (C)	83.6	363.439	30383.5004
Hydrogen (H_2)	12.4	1075.633	13337.8492
Sulfur (S)	0.5	190.798	95.399
Nitrogen (N_2)	1.0	4.14	4.14
Oxygen (O_2)	2.5	-86.308	-215.77
Ash	0.0	-21.1	0
Total	100		43605.1186

The specific exergy of gas fuels, according to Martinez and Casals [49] given by Eq. (2):

$$b = \rho \left[\Sigma x_i b_{qi} + RT_0 \Sigma x_i * \ln x_i \right] \qquad \text{(Eq. 2)}$$

Where *b* means the specific chemical exergy of the mixture in [kJ/kg fuel], Table 2 shows the exergy calculation for biogas in kJ per m^3 as an example of the exergy calculation of gas fuel. Biogas composition was taken from [43]. Equation 2 was used to perform all the exergy calculations for all gas fuels, and here Table 2 shows Biogas exergy calculation as an example of the exergy calculation of gas fuel.

Table 2. Biogas' chemical composition and its exergy calculation.

Biogas						
Component	Fraction Mol	b_q [kJ/mol]	Xi*b_{qi}	ln Xi	Xi * ln (Xi)	Units
Methane (CH_4)	0.6105	831.52	507.64296		0	
Ethane (C_2H_6)	0	1496.19	0		0	
Ethylene (C_2H_2)	0	1266.78	0		0	
Propane (C_3H_8)	0	2152.47	0		0	
Propylene (C_3H_6)	0	2003.22	0		0	
n-Butane (C_4H_{10})	0	2805.62	0		0	
n-Pentane (C_5H_{12})	0	3461.2	0		0	
Carbon dioxide (CO_2)	0.335	20.2	6.767	-1.0936577	-0.3663753	
Sulfur dioxide (SO_2)	0.0045	305.38	1.37421	-5.4038406	-0.0243173	
Nitrogen (N_2)	0.05	0.66	0.033	-2.9958225	-0.1497911	
Total	1		515.81717		-0.5404837	
Gas constant (R)					8.3144	[J/mol K]
T_0					298	[K]
$R*T_0 * \sum(X_i * \ln(X_i))$					-1339.1518	[J/mol]
$R*T_0 * \sum(X_i * \ln(X_i))$					-1.3391518	[kJ/mol]
Density (ρ)					44.61	[mol/m^3]
b_q					514.478018	[kJ/mol]
b					22950.8644	[kJ/m^3]

1.5. Energy grade function

According to Rosen [20], γ denotes the fuel energy-grade function, and *γ=b/HHV* is defined as the ratio of the specific chemical exergy of the fuel *b=[kJ/kg]* to the fuel's Higher Heating Value (*HHV*) = [kJ/kg].

Some authors have compiled exergy factors, which help estimate the exergy contents in different energy carriers [20], [27], [33], [69], [70]. However, these exergy factors (Table 3) could be different around the world and over time since chemical exergy depends on the chemical composition of the fuels, which varies over time and regions [67].

Table 3. Energy grade function around the world.

Fuel	**γ= b/HHV**	**γ= b/HHV**	**γ= b/HHV**	**γ= b/HHV**	**γ= b/HHV**	**HHV [kJ/Kg]**	**b [kJ/Kg]**	**γ= b/HHV**
Source	[33]	[20]	[27]	[69]	[70]	[70-84]	Own calculation	Own calculation
Coal and coal products	-	1.040	1.060	0.940	1.030	19432	19812	1.020
Oil, petroleum products	-	-	1.040	0.940	-	42725	42812	1.002
Coke	-	-	1.050	-	1.040	39421	39925	1.013
Natural gas +	-	0.930	1.030	0.960	0.940	37257	40023	1.074
CHP	-	-	-	0.620	-	-	-	-
Gasoline	-	0.990	-	-	0.990	51242	47547	0.928
Fuel-oil	-	0.990	-	-	0.990	43046	42102	0.978
Mechanical energy	1.000	-	1.000	-	-	-	-	-
Electrical energy	1.000	-	1.000	-	-	-	-	-
Chemical energy	about 1.0	-	about 1.0	-	-	-	-	-
Fuelwood	-	-	1.130	-	1.050	14486	15757	1.088
Nuclear energy	0.950	-	0.950	1.000	-	-	-	-
Sunlight	0.930	-	0.930	-	-	-	-	-
Hot stream (600 °C)	0.600	-	0.600	-	-	-	-	-
District heat (90 °C)	0.2 - 0.3	-	0.170	0.240	-	-	-	-
Heat at room temperature (20 °C)	0 - 0.2	-	0 - 0.1	-	-	-	-	-
Thermal radiation from Earth	0.000	-	0.000	-	-	-	-	-
Bagasse	-	-	-	-	-	7055	8672	1.229
Biomass	-	-	-	0.900	-	15223	16488	1.083
Gas condensate	-	-	-	-	-	52919	48214	0.911
Lubricant	-	-	-	-	-	50270	46934	0.934
Kerosene, Paraffin	-	-	-	-	-	43248	47739	1.104
Diesel	-	-	-	-	-	42283	43605	1.031
Liquefied Petroleum Gas	-	-	-	-	-	45961	41067	0.894
Petroleum coke	-	-	-	-	-	31110	33687	1.083
Biogas +	-	-	-	-	-	19930	22951	1.152
Blast - furnace gas	-	-	-	-	0.970	-	-	-

To be aware of these limitations, to carry out this research, Exergy factors were calculated (Table 4) according to the previous section (Exergy for fuels) for each energy carrier and year from 2003 to 2018. The reference-environment temperature used was 25 °C; the pressure was 1 atm. Input data were taken from [43], [68], [71]–[85]. Wall [33] pointed out that the exergy factor may exceed 1, depending on the definition of system boundaries and final states. When the exergy factor is greater than 1, it means that the exergy that we can obtain from these fuels is greater than the energy estimated by the calculation through the HHV. In practice, we overestimate the efficiencies by using the calorific value for calculations. Stepanov [65] pointed out that chemical exergies reflect more correctly and completely the energy potentials of fuels than the calorimetric values.

Table 4. Energy grade function of selected fuels in Mexico.

Fuel	**Coal**	**Oil**	**Coke**	**Natural gas**	**Gasoline**	**Fuel-oil**	**Fuelwood**	**Bagasse**	**Biomass**	**Condensate**	**Kerosene**	**Diesel**	**LPG**
2003	1.021	1.013	1.098	1.189	1.010	0.973	1.088	1.229	1.083	1.062	1.136	1.056	0.959
2004	1.021	0.999	1.098	1.132	1.010	1.118	1.088	1.229	1.083	1.062	1.097	1.024	0.959
2005	1.021	1.006	1.098	1.050	1.009	1.200	1.088	1.229	1.083	1.237	1.163	1.086	0.971
2006	1.021	1.019	1.098	1.048	1.009	1.201	1.088	1.229	1.083	1.237	1.453	1.303	0.971
2007	1.021	1.017	1.072	1.191	1.009	0.961	1.088	1.229	1.083	1.237	1.129	1.043	0.875
2008	1.021	0.981	1.072	1.194	1.009	0.937	1.088	1.229	1.083	0.991	1.114	0.990	0.860
2009	1.021	0.979	1.033	1.074	1.009	0.921	1.088	1.229	1.083	0.971	1.109	1.035	0.861
2010	1.020	0.980	1.164	1.123	1.009	0.947	1.088	1.229	1.083	0.966	1.091	1.037	0.859
2011	1.020	0.982	1.238	1.084	0.999	0.936	1.088	1.229	1.083	0.966	1.089	1.014	0.870
2012	1.020	0.987	1.061	1.088	1.004	0.953	1.088	1.229	1.083	1.035	1.095	1.043	0.876
2013	1.020	0.991	1.150	1.061	1.004	0.945	1.088	1.229	1.083	0.749	1.092	1.031	0.887
2014	1.020	0.992	1.061	1.056	1.001	0.957	1.088	1.229	1.083	0.733	1.098	1.049	0.868
2015	1.020	1.023	1.032	1.046	0.993	0.922	1.088	1.229	1.083	0.730	1.032	0.936	0.868
2016	1.020	1.023	1.032	1.050	0.958	0.918	1.088	1.229	1.083	0.730	1.027	0.976	0.881
2017	1.020	1.023	1.032	1.053	0.995	0.940	1.088	1.229	1.083	0.730	1.049	0.986	0.880
2018	1.020	1.023	1.032	1.074	0.919	0.942	1.088	1.229	1.083	0.730	1.000	0.972	0.880
Average	1.020	1.002	1.086	1.095	0.997	0.986	1.088	1.229	1.083	0.948	1.111	1.036	0.895

Tables 3 and 4 are inputs for the method developed in chapters 2 and 3 to analyze the exergy performance of Mexico from 2003 to 2018.

1.6. Conclusions

Exergy has a crucial role in industrial and economic development; however, inefficiencies, and exergy destruction, have led to critical environmental issues. The role of exergy in energy systems could have greater importance if exergy analyzes could be scaled from the traditional analyses. This chapter collated the methodology to calculate the specific fuel exergy, which was the basis for estimating the "Energy grade function" or "Exergy factor". These results will serve as input to exergy analysis for several analyses like exergy performance in the industrial and service sectors or to analyze the countries' whole economy or energy sector. Those results are shown in comparison against international data reported in the literature (Table 3). Tables 3 and 4 serve researchers who are interested in those data.

Exergy methods represent an improvement in evaluating the primary resources' exploitation, transformation, and use [7]. Hernandez and Cullen [37] conclude that exergy methods are flexible, integrated, and transparent. However, the current situation in the exergy analysis at a macro level is that studies exhibit wide variation in assumptions and methods. Sousa et al. [38] highlighted and synthesized significant differences in the methodologies used to account for societal exergy consumption. Although nowadays, there are factors left out of the analyses when considering the exergy balances of a country [32]. That is why chapter 2 developed a new approach to analyzing it.

Chapter 2. Exergy as a sustainable development indicator

2.1. Introduction

While economy-wide energy accounting can be accomplished from existing databases with only modest additional calculations and adjustments, only a portion of the information needed for national exergy accounting is available from national energy accounts. This chapter presents a new step-by-step approach for incorporating additional data and conducting other calculations required to include energy quality. Several previous papers were crucial for developing this method. The idea of national exergy balances comes from [54]. The energy grade function from [20], the exergetic cost from [86], the exergy intensity from [87], some ideas to handle the data from [27], and some inputs to create the exergy indicators come from [37].

The new approach to incorporating the exergy perspective into national accounting is a fresh perspective that brings an easy method to replicate around the world. Moreover, to contribute to sustainability analysis, several indicators have been proposed. i.e., Exergy intensity, Exergy used and Exergy destruction per capita, Internal exergy productivity, Exergy destruction per GDP, Entropy generated per capita, and Entropy generated per GDP. When possible, the results obtained here were compared with previous literature.

The methodology proposed in this document can be replicated and applied to analyze other countries. However, the information was structured based on the method indicated in the World Energy Balance Database from the International Energy Agency [88]. Other researchers who would like to replicate this methodology must ensure that their data information follows the guidelines; otherwise, adjust the data structure. This methodology's limitations and weaknesses are that the chemical exergy is calculated on its average (sections 1.3 and 1.4). This work assumes a homogeneity of the fuels – this thesis assumes average composition based on the most current data published by SENER (Department of Energy of Mexico and PEMEX).

2.2. A method to create exergy indicators

The method (Figure 3) begins with (1) energy balance data, (2) the chemical composition of the fuels, higher heating value (HHV), and flow mass rate, and (3) the country's economic data. This information is then organized using a matrix structure (Figure 4 and Table 12) to create an exergy balance. To do so, the specific exergy of each fuel must be estimated. Then carrying out the exergy balance is possible, the exergy destroyed, and the efficiencies are calculated. Finally, the exergy indicators are calculated.

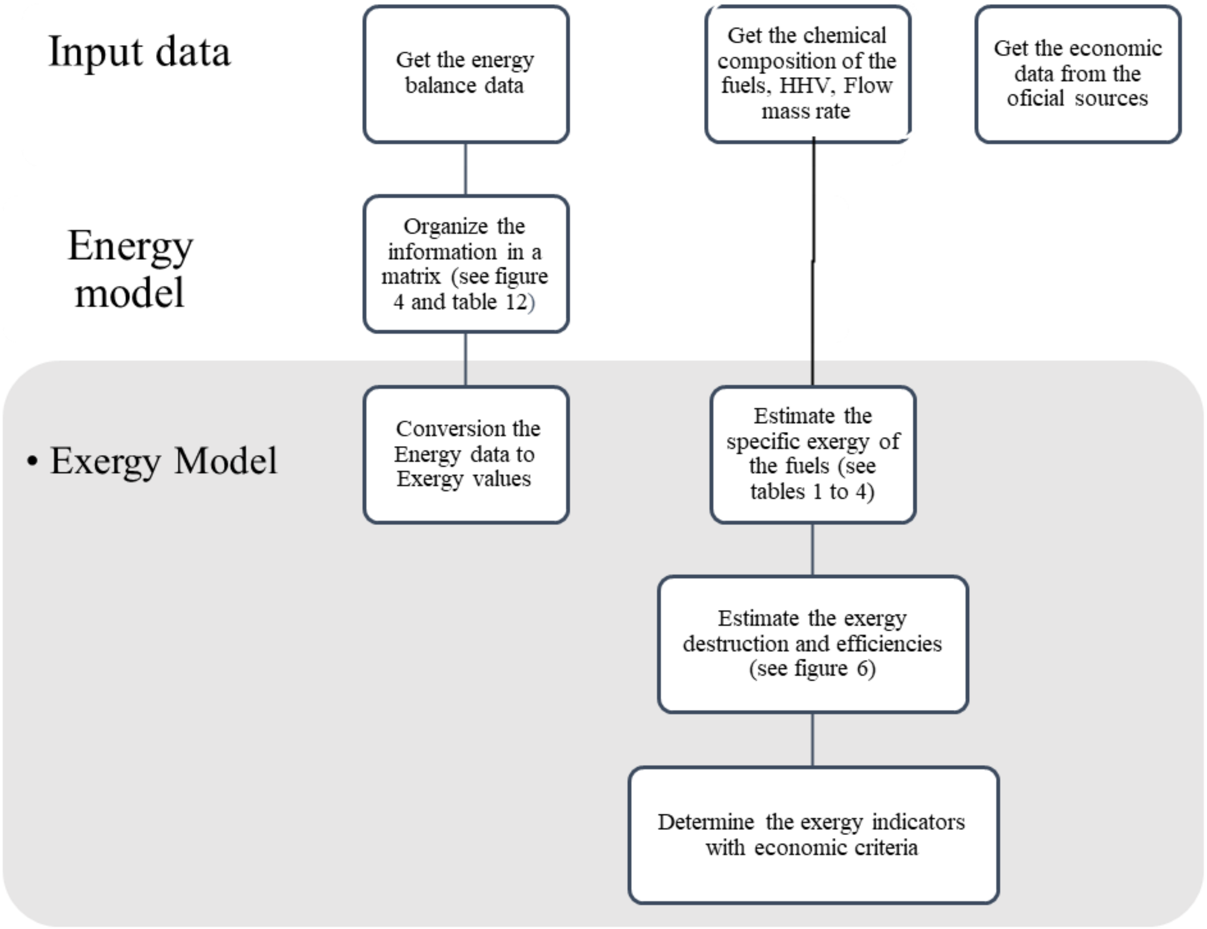


Figure 3. Flowchart of the overall methodology used to calculate the exergy indicators.

Data for this analysis was taken from the following sources: The Department of Energy of Mexico (SENER, Spanish acronyms), the Mexican state oil company (PEMEX, Spanish acronyms), and the World Bank (WB). Information related to the current National Energy Balance of Mexico (NEB) for the years 2003-2018 was taken from SENER publications [43], [71]–[85]. The average chemical composition for fuels was obtained from [43], [68], [71]–[85]. Gross Domestic Product and total population were collected from World Bank [89].

All energy carriers' exergy factors were calculated in concordance with Sections 1.3 and 1.4. Subsequently, the exergy balance of the energy system was carried out, being compatible and comparable with the energy balance previously done. Exergy efficiency and exergy destruction were calculated according to the standard exergy balance [5], [90]–[92]. Finally, economic indicators were introduced to the analysis. Figure 4 shows all the flows (58) and processes (14) analyzed in this research (see Table 12). Where, F_i = mass, energy, or exergy flows, P_i = energy sector processes, EU = End users, AES = Another energy system. The primary challenge in creating a national exergy balance is identifying exergy destruction occurring at each state of the energy balance. Each state presents different methodological challenges, and therefore different methodologies were required. The remainder of this section discusses the methodologies used in each stage of the exergy balance calculation.

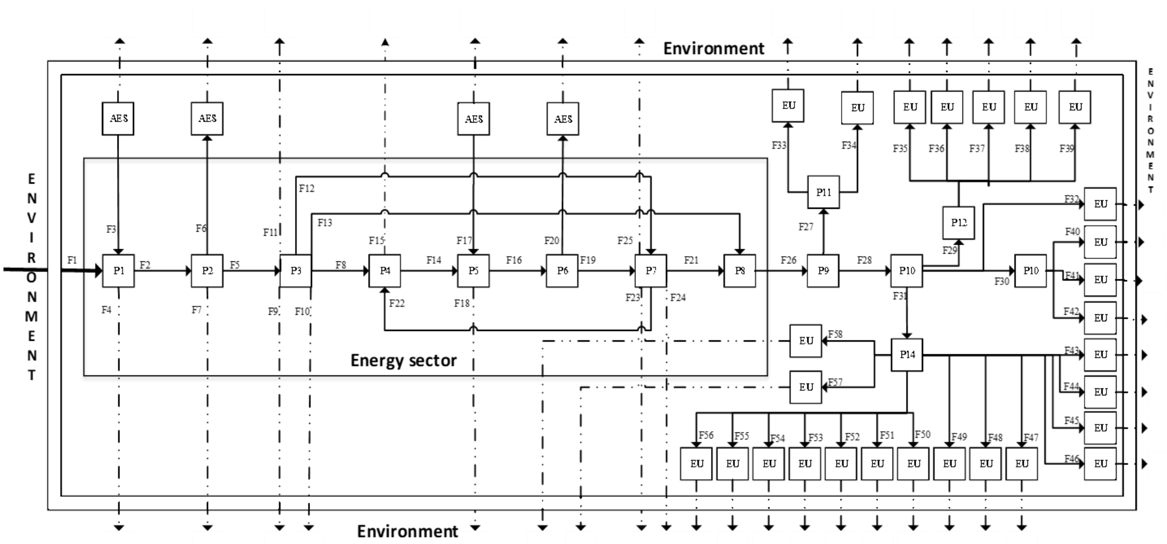
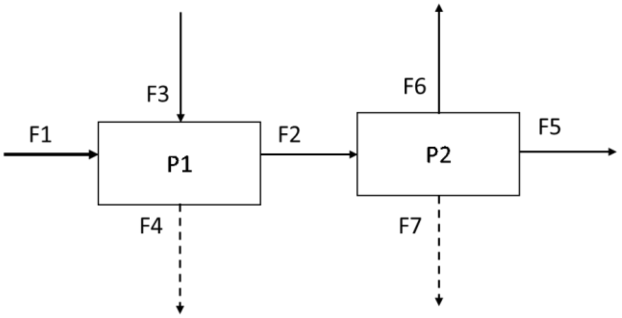


Figure 4. Graphical representation of the National Balances of Mexico.

The matrix **[*A*]** represents the physical structure of the national balances, and it is constituted of rows (processes) and columns (flows) that correspond to the connections between the mass, energy, or exergy flows. The elements a_{ij} take the value of [+1, -1 or 0]. If the flow "j" enters the process, the value will be +1. If the flow "j" goes out of the process, the value will be –1. If the flow "j" is not going through that process, the value will be 0. If the flow "j" is not going through that process, the value will be 0. Figure 5 shows the interconnection of the mass, energy, or exergy flows through the processes and the matrix's graphical representation of the two processes.



$$\begin{array}{c|cccc} P_i/F_i & F1 & F2 & \cdots & Fn \\ P1 & 1 & -1 & \cdots & a_{1n} \\ P2 & 0 & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ Pm & a_{m1} & a_{m2} & \cdots & a_{mn} \end{array}$$

Figure 5. Structure of the flows and processes. Where F_i = mass, energy, or exergy flows, P_i= Energy sector processes.

Multiplying the matrix [A] by different vectors allows us to estimate the efficiency and the exergy destruction where the vectors are [E]=Energy, [B]=Exergy, and the exergetic cost [B*] (see Figure 6. The parameters "α", "w", were calculated with the methodology of the theory of exergetic cost proposed by [86].

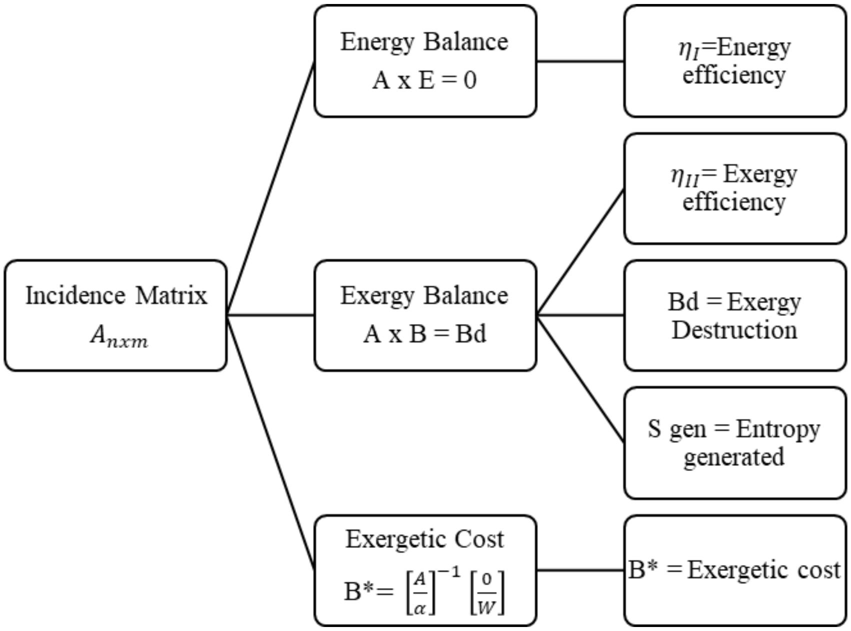


Figure 6. Description of the procedure to carry out the balances. It shows how matrix [A] was used to calculate the energy balance, the exergy balance, and the exergetic cost.

The mass flows rates that make up the National Energy Balance (NEB) were calculated: All the flows that belong to the NEB are reported in [PJ] as the standard unit. The information was arranged in a matrix to work with it as vectors. According to Cengel [5], the energy balance is the following: $\sum_{Input}^{n} E_{Input} - \sum_{Output}^{k} E_{Output} = 0$. The energy vector [E] represents all the energy flows per year. The multiplication $A\ X\ E = 0$ means that energy inputs and outputs are the same. The energy efficiency of the energy sector was estimated as in Eq. (3) [20].

$$\eta_I = \left(\frac{Energy\ input - Energy\ losses}{Energy\ input}\right) = \frac{(Domestic\ energy\ supply + Secondary\ energy\ imports) - (energy\ loses)}{(Domestic\ energy\ supply + Secondary\ energy\ imports)}$$

(Eq. 3)

To elaborate on *National Exergy Balance (NBB) of Mexico*, first, the flows and processes were identified (see annex A); then, according to Cengel [5], the exergy flows of fuels (B) were calculated with the mass flow rate (m) and the specific exergy [b] by $B_i = (\ b_i)(m_i)$; the exergy of different flows were estimated using factors shown in Tables 3 and 4.

$$\begin{gathered} B_{F_1} = \sum_i^n \left(b_{i_{F1}} * \left(m_{i_{F1}}\right)\right) = \sum_i^n \left(\gamma_{i_{F1}} * \left(E_{i_{F1}}\right)\right) \\ B_{F_2} = \sum_i^n \left(b_{i_{F2}} * \left(m_{i_{F2}}\right)\right) = \sum_i^n \left(\gamma_{i_{F2}} * \left(E_{i_{F2}}\right)\right) \\ \vdots \\ B_{F_{58}} = \sum_i^n \left(b_{i_{F58}} * \left(m_{i_{F58}}\right)\right) = \sum_i^n \left(\gamma_{i_{F58}} * \left(E_{i_{F58}}\right)\right) \end{gathered} \qquad \text{(Eq. 4)}$$

By multiplying the incidence matrix [***A***] by the vector of exergy [***B***], the diagnosis vector is obtained [***Bd***], which expresses the irreversibility of each process. Exergy destruction is obtained as follows: $A\ X\ B = Bd$. The exergy destroyed in the system is directly proportional to the entropy produced due to irreversibilities within the system. The proportionality constant is the absolute temperature of the environment. The theorem holds regardless of any heat interaction between the system and the environment [6]. Exergy is nonconservative. The model $\sum_{Input}^{n} B_{Input} - \sum_{Output}^{k} B_{Output} = Bd$ represents the exergy balance for each process [86]. Each of them will be a component of the vector ***Bd.***

To contribute to the sustainability analysis, indicators have been proposed. Exergy efficiency and Exergetic cost come from the exergy analysis. In addition, other indicators combine the exergy results (obtained from section 3.4) with the economic data of a country (GDP and population), i.e., Exergy intensity, Exergy used and Exergy destruction per capita, Internal exergy productivity, and Exergy destruction per GDP.

According to Reistad [54], the exergy efficiency of the energy sector was estimated as Eq. (5).

$$\eta_{\mathrm{II}} = \left(\frac{\text{Exergy input - (Exergy losses + Exergy destruction)}}{\text{Exergy input}}\right) \quad \text{(Eq. 5)}$$

The exergetic cost [B*] of a flow, fuel, or product is the quantity of exergy needed to produce it. The exergetic cost includes the exergy content in the product plus the necessary exergy to obtain the product. **B*** always will be greater than the exergy content of the product. The exergetic cost was calculated following the methodology of the theory of exergetic cost proposed by [86].

Exergy intensity measures the amount of exergy used per unit of economic output. To calculate this indicator, the ratio of the exergy consumed by a country between the level of total production measured by the GDP was estimated, according to Hernandez and Cullen [37], see Eq (6).

$$Exergy\ intensity\ =\ Final\ exergy\ consumption\ /\ GDP \qquad \text{(Eq. 6)}$$

The exergy per capita is the amount of useful energy to satisfy the needs of society. This indicator was estimated as Eq (7).

$$Exergy\ used\ per\ capita\ =\ Final\ exergy\ consumption\ /\ total\ population \qquad \text{(Eq. 7)}$$

Exergy destroyed per capita shows the energy resources society loses per inhabitant, which never will return. It is calculated by Eq. (8).

$$Exergy\ destruction\ per\ capita\ =\ Exergy\ destruction\ /\ total\ population \ \text{(Eq. 8)}$$

Exergy destruction per GDP can be seen as a measure of operational and economic efficiency because it is the ratio between the part of exergy wasted into the environment by every unit of economic output. It is calculated according to Eq. (9).

$$Exergy\ destruction\ per\ GDP\ =\ Exergy\ destruction\ /\ Gross\ Domestic\ Product \ \text{(Eq. 9)}$$

Internal exergy productivity reflects the amount of economic output generated by each unit of primary exergy production, Eq. (10). This means how much economic wealth was generated in the country by each unit of exergy extracted from the environment on national territory.

$$Internal\ exergy\ productivity\ =\ GDP\ /\ Primary\ Exergy\ Production \qquad \text{(Eq. 10)}$$

Entropy generated per GDP could be visualized to measure the degradation of the environment per unit of economic output. It is calculated according to Eq. (11).

$$Entropy\ generated\ per\ GDP = Entropy\ increase\ /\ GrossDomestic\ Product \qquad \text{(Eq. 11)}$$

Entropy generated per capita measures the energy waste emitted into the environment per inhabitant. It is calculated by Eq. (12).

$$Entropy\ generated\ per\ capita = Entropy\ increase/\ total\ population \qquad \text{(Eq. 12)}$$

2.3. A new approach to analyzing the energy systems

The World Development Indicators are a compilation of relevant and internationally comparable global development statistics [89]. Here this chapter proposes a set of exergetic indicators that combine economic and technical criteria to provide an alternative lens into the overall performance of an economy. These databases include social, economic, energy, and environmental data. Population and GDP data were taken from [89] to create the new indicators. The base year 2010 was used to make the results comparable with indicators reported by the World Bank. This section shows the results obtained by applying the method proposed in the previous section to the Mexican energy sector from 2003 to 2018.

2.3.1. Exergy production and consumption

Mexico is considered a developing country. Like many countries, Mexico aspires to develop sustainably. However, Mexico´s energy supply exhibits significant contradictions. Mexico has the world´s third-largest solar potential and sizable wind energy resources, but almost all of the primary exergy supply relies on fossil fuels [93]. Table 5 summarizes the primary energy supply of Mexico, and then it shows the exergy factors used to estimate the exergy flows. So, it shows the transformation from the energy perspective into the exergy perspective, changing the “Primary energy production” to the “Primary exergy production”. It should be noted that this method was done for all flows represented in Figure 4 and Table 12.

Table 5. Primary energy and exergy production of Mexico 2003-2018.

Primary energy production. Source data: [43], [71]–[85].

Energy carrier	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Unit
Coal	184	246	254	283	306	290	255	306	392	311	300	304	288	254	308	280	PJ
Oil	7609	7763	7574	7304	6923	6521	6075	6009	5934	5919	5815	5597	5068	4827	4355	4046	PJ
Condensate	131	153	184	141	107	91	86	93	100	88	134	106	99	88	67	49	PJ
Natural gas	1684	1594	1856	2075	2135	2290	2390	2204	2118	2029	2046	2079	2037	1780	1518	1279	PJ
Nuclear	115	101	118	119	114	107	113	64	106	91	123	101	120	110	113	156	PJ
Hydro	71	90	99	109	97	140	95	132	131	115	101	140	111	111	115	117	PJ
Geo	135	149	165	151	168	160	153	150	149	133	131	130	165	133	127	113	PJ
Solar	3	3	2	2	3	3	4	5	6	7	8	9	10	11	15	24	PJ
Wind Energy	0	0	0	0	1	1	7	4	6	13	15	23	31	37	39	47	PJ
Biogas	0	0	0	0	1	1	1	1	1	2	2	2	2	2	3	3	PJ
Bagasse	90	93	105	98	100	99	89	89	91	95	124	109	107	110	117	122	PJ
Fuelwood	267	267	266	266	293	262	261	259	258	257	255	254	253	252	250	249	PJ
Others	0	0	0	0	0	0	1041	667	628	772	739	735	761	887	-1	0	PJ
Total	10289	10459	10624	10551	10248	9965	10570	9984	9921	9831	9792	9590	9052	8601	7027	6485	PJ

Energy grade function

Energy carrier	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Average
Coal	1.021	1.021	1.021	1.021	1.021	1.021	1.021	1.020	1.020	1.020	1.020	1.020	1.020	1.020	1.020	1.020	1.020
Oil	1.013	0.999	1.006	1.019	1.017	0.981	0.979	0.980	0.982	0.987	0.991	0.992	1.023	1.023	1.023	1.023	1.002
Condensate	1.062	1.062	1.237	1.237	1.237	0.991	0.971	0.966	0.966	1.035	0.749	0.733	0.730	0.730	0.730	0.730	0.948
Natural gas	1.189	1.132	1.050	1.048	1.191	1.194	1.074	1.123	1.084	1.088	1.061	1.056	1.046	1.050	1.053	1.074	1.095
Nuclear	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Hydro	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Geo	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Solar	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Wind Energy	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Biogas	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152	1.152
Bagasse	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229	1.229
Fuelwood	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088	1.088
Others							1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000		

Primary exergy production

Energy carrier	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Unit
Coal	188	251	260	289	312	296	260	312	400	317	306	310	293	259	314	285	PJ
Oil	7705	7753	7619	7441	7044	6398	5946	5887	5828	5840	5765	5553	5184	4937	4455	4139	PJ
Condensate	140	163	227	175	133	91	84	89	97	91	100	78	72	64	49	36	PJ
Natural gas	2002	1805	1949	2173	2543	2735	2567	2475	2295	2207	2170	2197	2131	1869	1598	1374	PJ
Nuclear	115	101	118	119	114	107	113	64	106	91	123	101	120	110	113	156	PJ
Hydro	71	90	99	109	97	140	95	132	131	115	101	140	111	111	115	117	PJ
Geo	135	149	165	151	168	160	153	150	149	133	131	130	165	133	127	113	PJ
Solar	3	3	2	2	3	3	4	5	6	7	8	9	10	11	15	24	PJ
Wind Energy	0	0	0	0	1	1	7	4	6	13	15	23	31	37	39	47	PJ
Biogas	0	0	0	1	1	1	1	1	2	2	2	2	2	2	3	3	PJ
Bagasse	111	114	129	121	122	122	109	109	111	117	152	134	132	135	144	150	PJ
Fuelwood	290	290	290	290	319	285	284	282	281	279	278	276	275	274	272	271	PJ
Others	0	0	0	0	0	0	1041	667	628	772	739	735	761	887	-1	0	PJ
Total	10760	10720	10858	10872	10857	10339	10665	10180	10040	9984	9891	9688	9287	8830	7245	6715	PJ

Figure 7 shows the annual primary exergy production by energy carrier, 92% of primary exergy production comes from coal, natural gas, or oil. Intensive use of these resources produces pollutants that influence air quality and are the primary source of Mexico's greenhouse gas emissions.

Mexico experienced a drop in primary exergy production from 10,759 PJ in 2003 to 6,714 PJ in 2018. This drop in exergy production is mainly due to a reduction in oil production. Oil production has dropped in Mexico for 16 consecutive years. In 2003, Mexico produced 3.37 million barrels of oil per day. Production decreased to 1.7 million barrels per day in 2018. The drop is due mainly to a lack of investment in exploration and production. 94% of oil production in Mexico is carried out by the oil state company PEMEX.

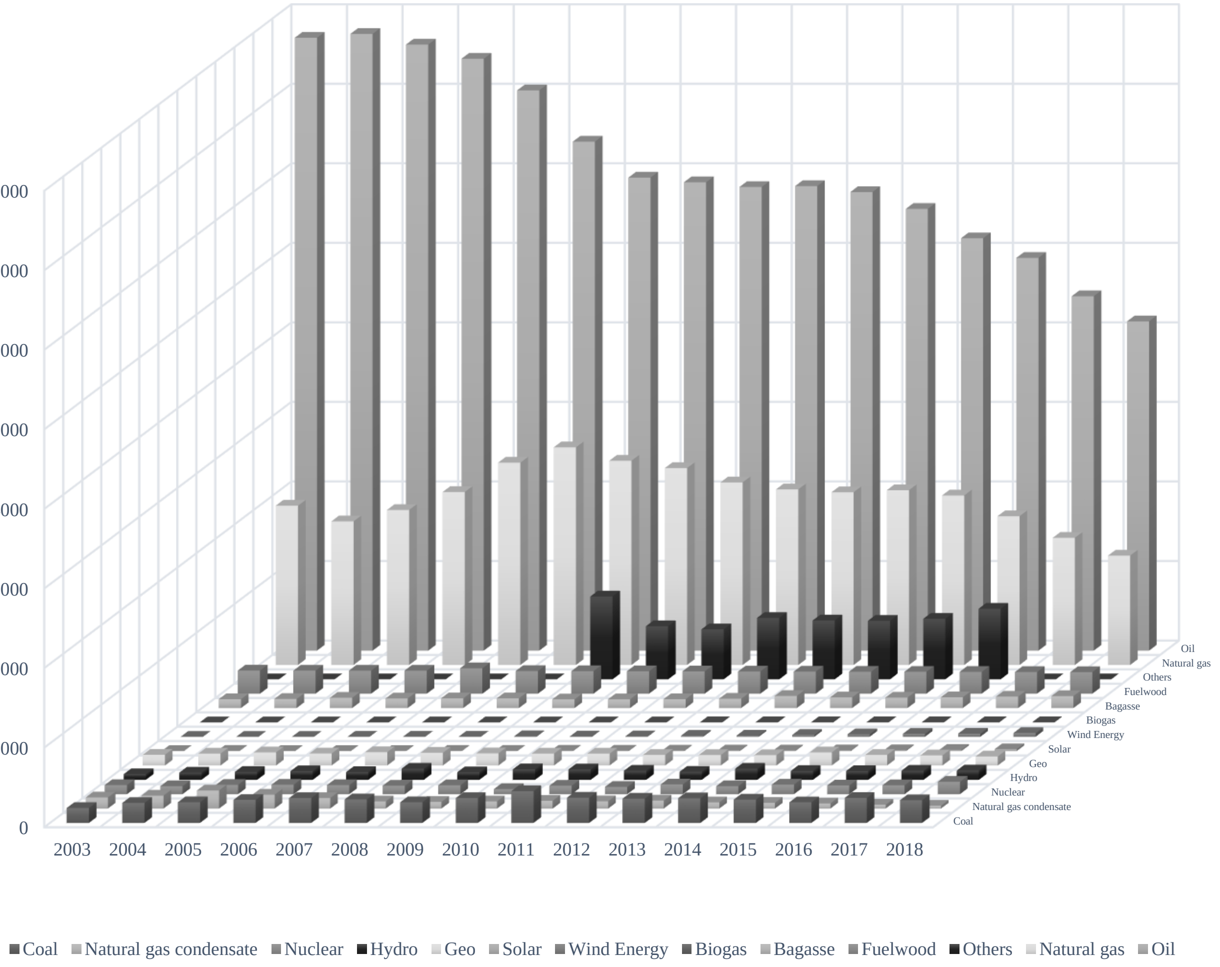


Figure 7. Primary exergy production in Mexico in PJ.

Figure 8 shows the final exergy consumption. Final exergy consumption increased from 4,218 PJ in 2003 to 5,092 PJ in 2018. The growth of the Mexican economy can largely explain this increase. Mexico's gross domestic product grew 2.6% on average from 1990 to 2018. There was a 4.7% drop in 2009 due to the 2008 financial crisis. This economic contraction was also reflected in reduced exergy consumption in 2008. Final exergy consumption also decreased in 2015, due to a drop in oil prices, from 112 USD per barrel in June 2014 to 53 USD per barrel in January 2015. The price adjustments, and the decline in oil production, impacted the national exergy consumption. A drop in oil prices should increase oil consumption.

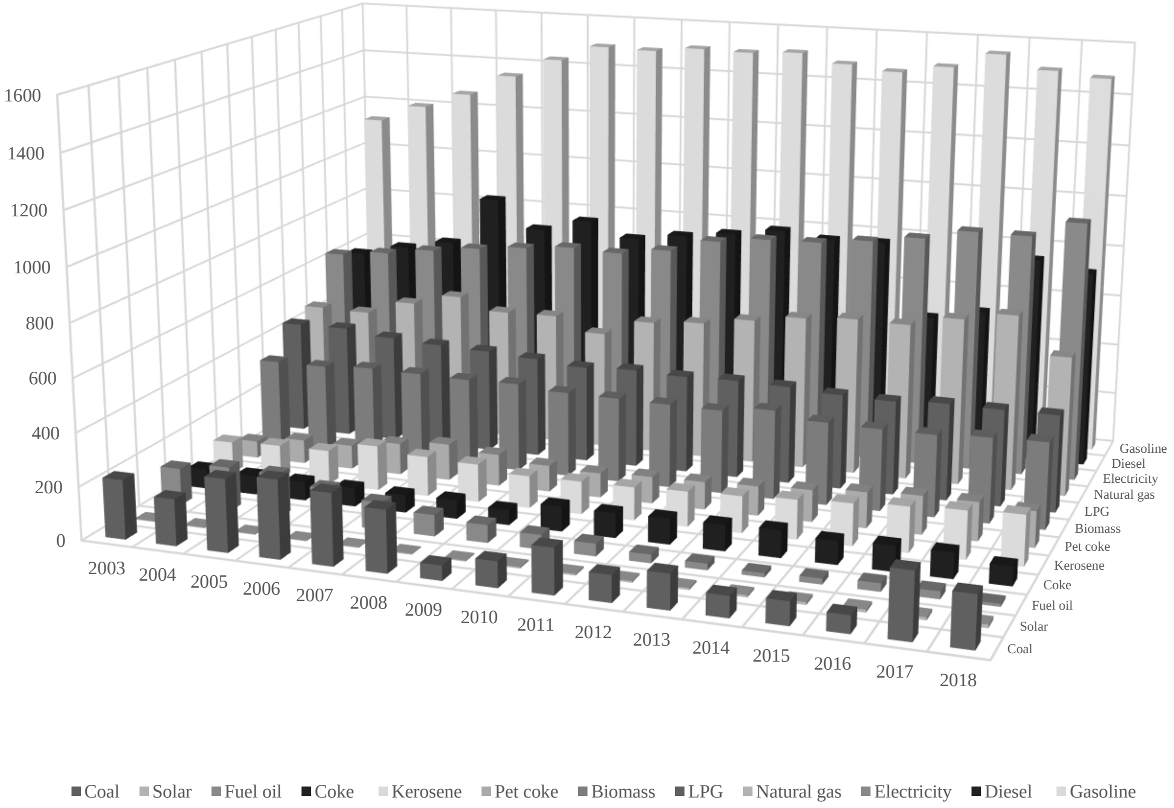
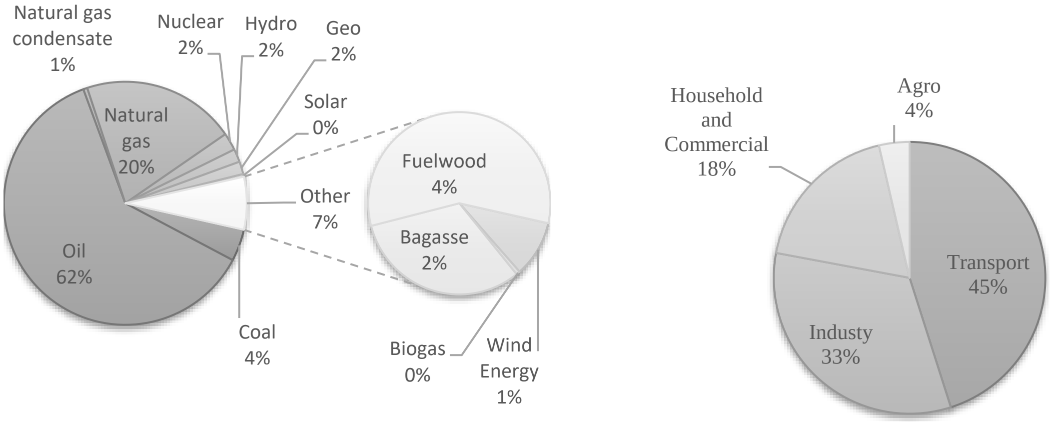


Figure 8. Final exergy consumption in Mexico in PJ.

Mexico is an oil-exporting country; oil revenues represent 30% of Government revenue. Therefore, the drop in oil prices meant a cut in public income; consequently, a cut in Government expenditure and investment explains a contraction in aggregate demand. Additionally, in Mexico, a special tax on gasoline (IEPS) sets the price of gasoline regardless of the international oil price. If the international oil price falls, gasoline is charged more tax. If the global price of oil rises, gasoline is charged less tax, which can explain this reduction in energy consumption.

Mexico's energy system has more significant potential to become sustainable by incorporating renewables and changing the current trend in exergy supply. The country has abundant access to fossil fuel sources and renewables as well [93]. Primary exergy consumption in the Mexican energy matrix in 2018 comprised 46% oil, 40% natural gas, 6.9% coal, 1.32% nuclear power, 3.8% hydroelectric, and 2.3% other renewable energy sources (Figure 9). Arango Miranda et al. [94] made a Kuznets curve analysis; they revealed Mexico's outcomes that increasing renewable exergy share will decrease CO_2 emissions.



(a) *Primary exergy consumption by fuel* *(b) Final exergy consumption by sector*

Figure 9. Exergy consumption in Mexico in 2018.

Most exergy exports correspond to oil (primary exergy). The natural resources rents are a country's income when selling its resources. The income is equal to the price of a commodity minus the cost of producing them [89]. State income derived from fossil fuel rents as a percentage of GDP was 3.44 % in 2003, 5.99% in 2011, and 1.82 in 2017. Fossil resources' rents are the most important income of the total natural resources' rents, representing 96 % in 2003 and 63 % in 2017. Table 6 shows the rents of Fossil fuels, Natural resources as % of GDP, and Fossil fuels exports as % of the total exergy exports for Mexico from 2003 to 2017. Nowadays, there is no market for exergy or exergy destroyed. Mexico is losing various GDP points because of exergy destruction. Exergy destruction could have an avoidable economic impact if efficiency is increased.

Table 6. Natural resources rents in Mexico as a percentage of GDP, and Fossil fuels exports as a percentage of the total exergy exports. Source data: [89].

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Oil rents (% of GDP)	3.33	4.18	5.50	5.70	5.11	5.98	3.41	4.11	5.61	5.34	4.72	3.93	1.61	1.22	1.72
Natural gas rents (% of GDP)	0.10	0.11	0.14	0.18	0.18	0.20	0.31	0.19	0.25	0.27	0.26	0.18	0.12	0.07	0.08
Coal rents (% of GDP)	0.01	0.03	0.03	0.04	0.03	0.11	0.05	0.07	0.13	0.06	0.04	0.03	0.01	0.02	0.02
Total natural resources rents (% of GDP)	3.56	4.51	5.94	6.38	5.87	6.79	4.26	5.19	7.19	6.85	6.03	5.01	2.54	2.28	2.88
Oil, carbon, and natural gas exports as % of total exergy exports	95.1	95.4	95.1	92.5	92.0	89.9	85.4	87.1	88.2	89.5	86.7	85.2	85.8	87.6	88.4

2.3.2. The overall energy and exergy efficiency of the Mexican economy

Energy losses in Mexico´s energy sector in 2018 (3,036 PJ) were 29 % of the energy production or 63% of the size of Mexico's energy exports (3030 PJ) (Figure 10). In contrast, the exergy balance of Mexico shows that the exergy destroyed in 2018 was 58 % of the exergy production or 125 % the size of Mexico's exergy exports. In other words, exergy destruction was larger than exergy exports. The left side of Figures 10 and 11 shows the total energy and exergy inputs extracted from the environment (primary) or another energy system (imports); the middle shows the processes that belong to the energy sector, and the right side shows the exportations, exergy destroyed, and the final supply of exergy by each end-user.

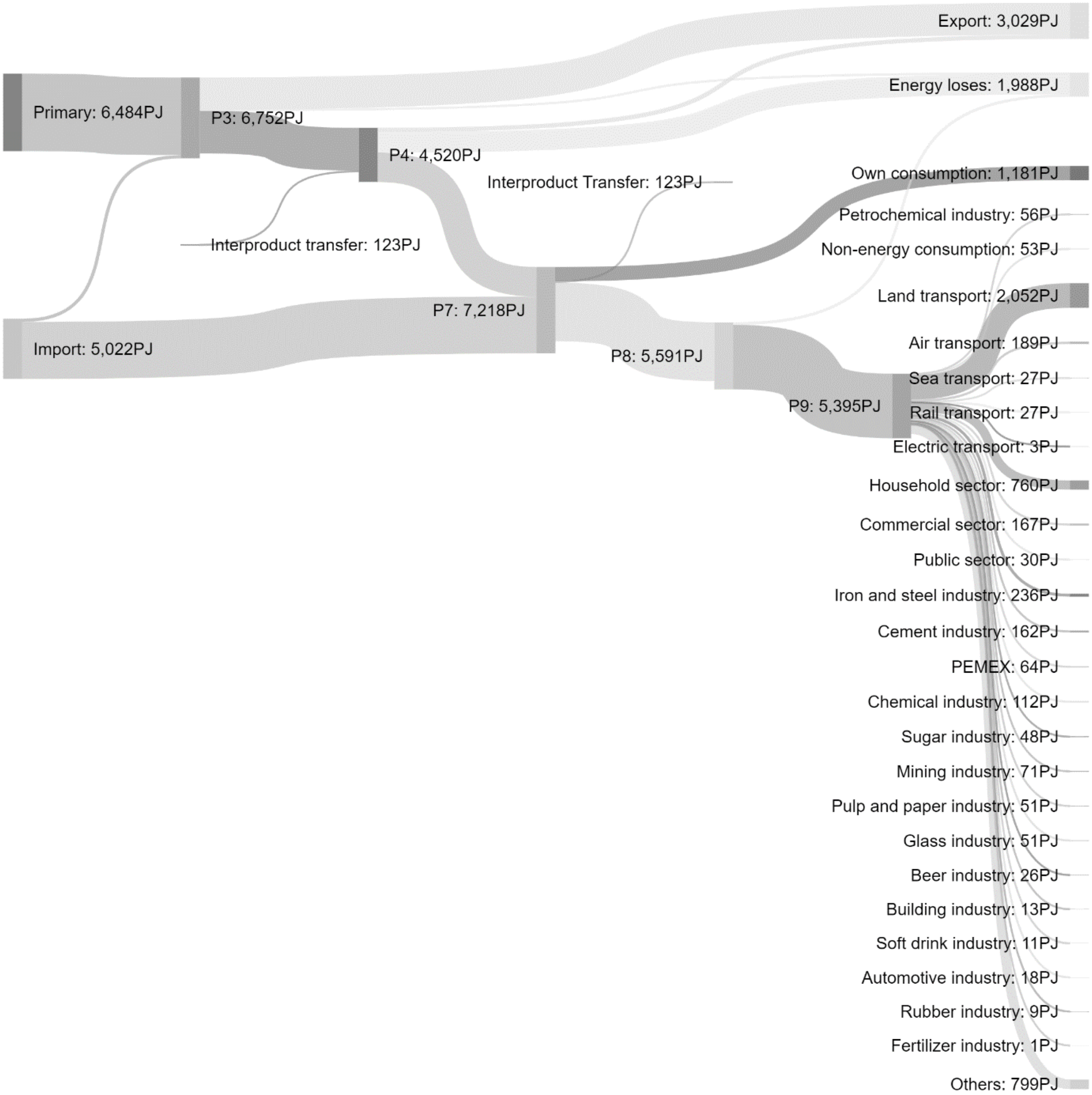


Figure 10. Energy flows in Mexico for 2018 in PJ.

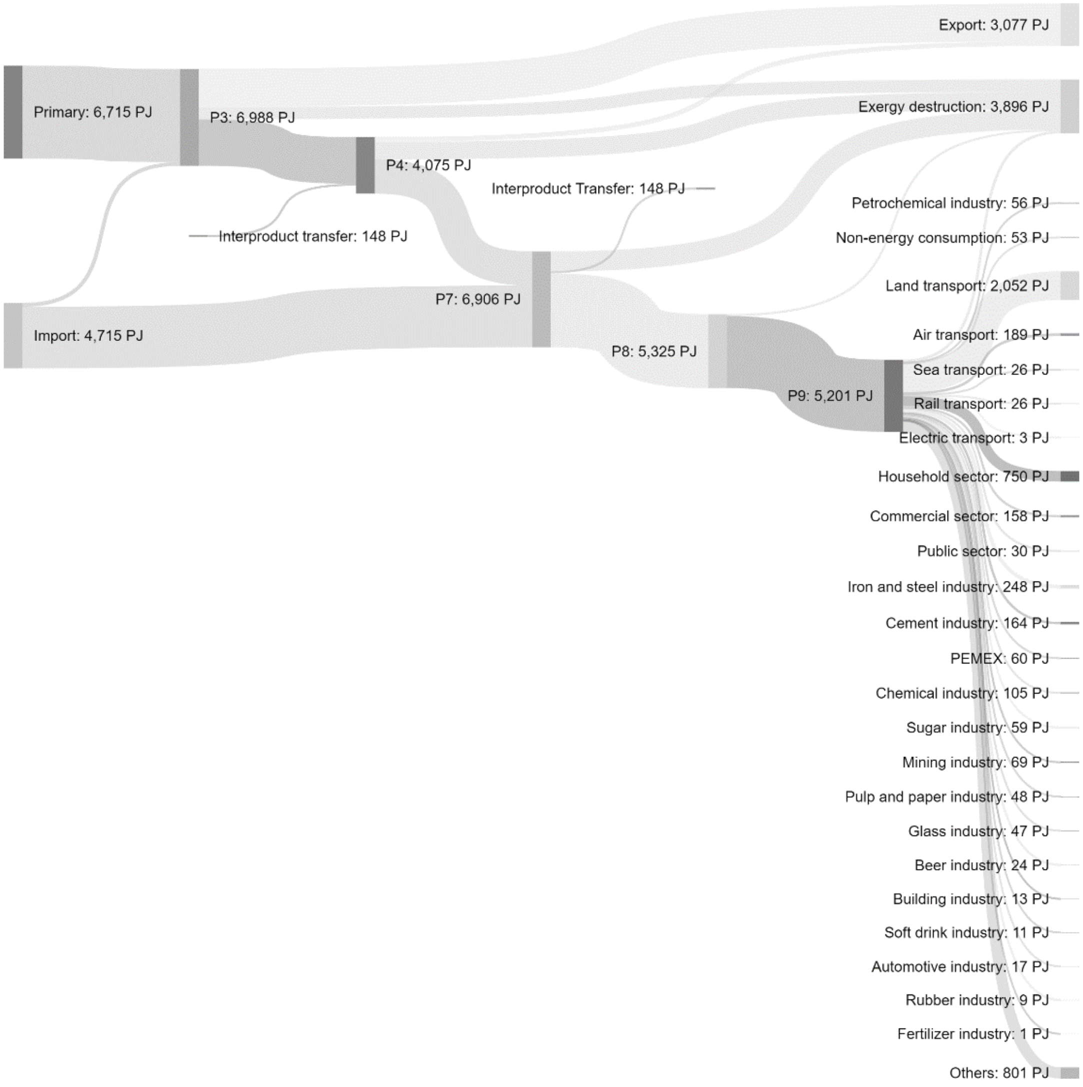


Figure 11. Exergy flows in Mexico for 2018 in PJ.

Energy system analysis and efficiency have become more critical than in the past because natural energy sources are limited [91], [95], and they face critical adverse climate impacts [96], [97]. However, the loss of energy in the current National Energy Balance is noted but not discussed in depth. The exergy method can measure exergy efficiency [98]–[100] and complement the current analysis.

According to the current national energy balance, the efficiency of the energy sector (as Eq. 4) in Mexico was 75.22 % in 2003 and 83.46 % in 2018 (see Figure 12); therefore, this efficiency by itself is not an accurate performance measurement [5], [91], [92]. Because energy consists of two parts, exergy and anergy. Exergy measures the part of the energy that may be transformed into other forms without restrictions [45], [70], [101]–[104]. Electricity, for example, has 100 % exergy. This means that it can be completely exploited. In contrast, fossil fuels – coal, gas, and oil cannot be transformed 100 % into work. Baehr [105] introduced the concept of anergy as a non-transformable part of energy: $Anergy = T_0(S - S_0)$.

Quantitatively, this the relationship between energy and exergy. It is represented by: $Energy = Exergy + Anergy$ [45], [48], [70], [101]–[104]. Therefore, the discussed of concept of anergy is not used in the present work.

To overcome this deficiency, efficiency based on the exergy perspective provides a better measurement of the work extracted from the resources [106]. As the second law states, the efficiency of the energy sector (as Eq. 5) in Mexico was 60.56 % in 2003 and 59.27 % in 2018 (See Figure 12),

By contrasting exergy analysis with conventional energy analysis, this research reveals that the amount and quality of energy losses are more significant than previously thought. The energy efficiency of the energy sector (as Eq. 3) in Mexico was 75% in 2003 and 83% in 2018. In contrast, exergy efficiency (as Eq. 5) was 61% in 2003 and 59 % in 2018, or roughly 20% lower than energy efficiency (Figure 12). In addition, while energy efficiency rose between 2014 and 2018, exergy efficiency decreased, indicating that energy analysis provided an inaccurate assessment of efficiency trends in the Mexican energy sector. Nevertheless, it also means there is room to improve efficiency.

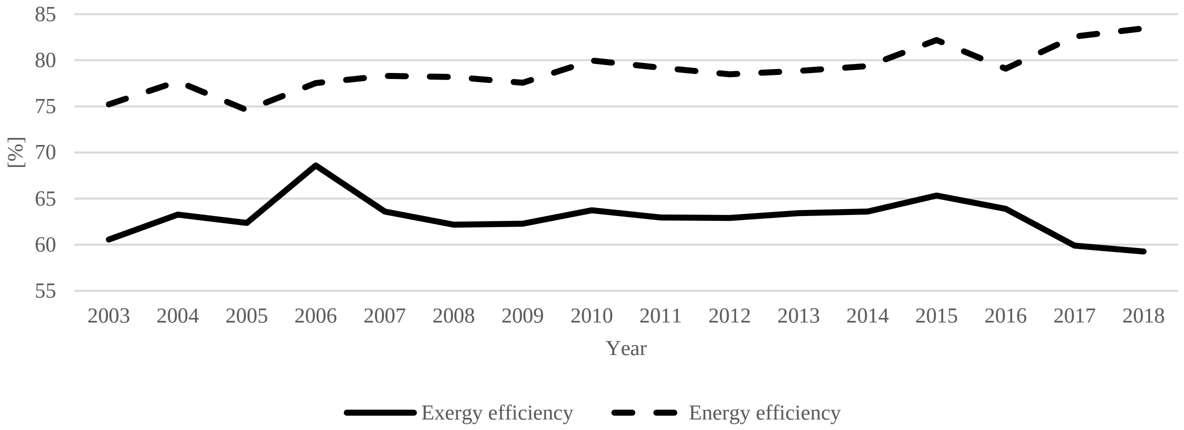


Figure 12. Exergy efficiency versus energy efficiency in Mexico.

It is challenging to compare exergy efficiency across different countries because of differences in industrial structures and energy sectors, the lack of data, the inconsistency in the information, methodological differences, and the level of disaggregation [38]. Nonetheless, some results are comparable. The notion that exergy efficiency is lower than energy efficiency is consistent across studies. It can also be said that the exergy efficiency of Mexico's energy sector is around 60%. Previous research indicates that the exergy efficiency by end-users is about 20% [55], which would be consistent with the information presented here. This work performs the exergy analysis in the energy sector, which means when the final consumer receives the energy. Guevara's work analyzed the end-user's efficiency during the final consumption. The integration of these two works complements the analysis of what is happening in the Mexican energy system.

It is also challenging to compare exergy efficiency across economies. For comparison, Wall determined that the overall exergy efficiency of Sweden was 14% in 1994 [107], the efficiency of Japan was 21% in 1985 [19], and the efficiency of Italy was 18% in 1990 [33]. Ertesvåg [21] estimated the overall efficiency of the Norwegian economy at 24% in 2000. However, all of them are not comparable at all with the methodology that was proposed here in this research. Because those countries were analyzed under the extended exergy method, which covers the entire economy, energy, and other resources like labor, capital, and natural resources, these elements are not considered within the scope of this research.

Exergy destruction in Mexico has increased over the last decade (Figure 13), but there are opportunities to minimize the loss of energy quality. These potential improvements could be managed by trying to reduce the technical irreversibilities during the processes. This work helps us identify the amount of energy quality destroyed in Mexico. To make more specific proposals on the actions necessary to avoid energy loss and exergy destruction, each industrial branch or sector requires more specific analyses (in both energy and exergy approaches). For example, Islas-Samperio et al. [108] concluded that Mexico's transport sector could be decarbonized using measures such as traffic optimization, vehicle energy efficiency, increasing the use of electric cars, and substituting fossil fuels for biofuels. Oropeza and Petzold [109], with an approach that embraces the use of efficient devices and the reduction of the time of use in the residential sector, a maximum energy saving of almost 20 TWh is estimated, which is 36% of the total electricity use of the Mexican residential sector in 2015. All these actions help to save exergy and avoid exergy losses and exergy destruction.

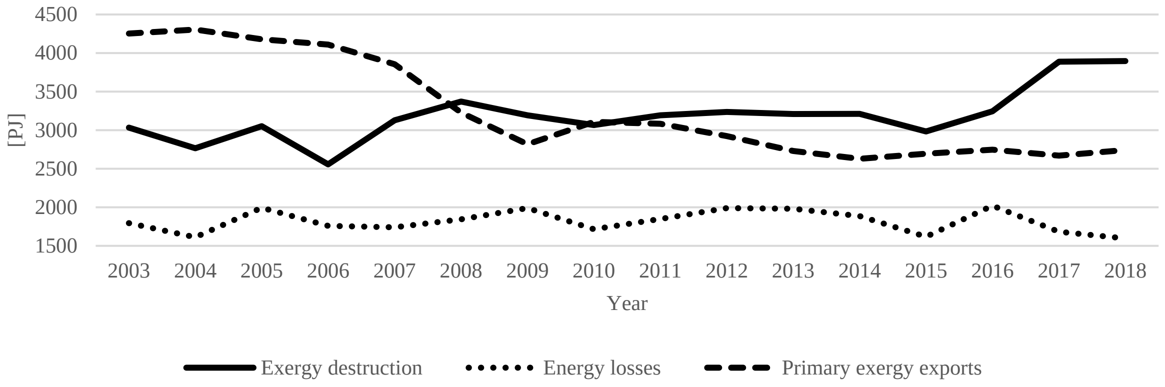


Figure 13. Annual Exergy destruction and Energy losses in Mexico.

Each exergy loss or destruction represents an economic loss. Indeed, the quantity of exergy destruction is more significant than the total exergy export amount. The income from Mexico's exports represented 2.9 % of Mexico's 2017 GDP.

The exergetic cost represents the amount of exergy necessary to generate the product; it can be used as an indicator of the exergy efficiency [86]. The ratio "Total final exergy supply / Exergetic cost of the total exergy supply" was calculated as a measure of exergy efficiency; compared with the energy sector's exergy efficiency (as in Eq. 5), they are similar and oscillate around 0.62 (see Figure 14).

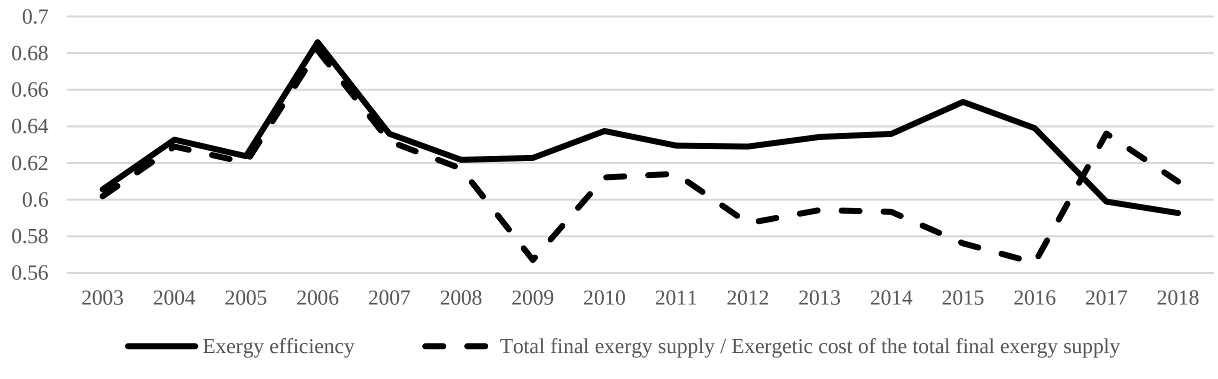


Figure 14. The exergy efficiency of the energy sector of Mexico.

The relation "total exergy supply / exergetic cost of the final exergy supply" shows the final exergy output to the necessary exergy, a global efficiency of the system measured in for its production, representing the conceptual framework of the Second law of thermodynamics. Figure 14 shows that this ratio and the exergy efficiency are very similar, and it would be desirable that both indicators become close to one to be more efficient.

2.3.3. Exergy intensity

While energy intensity provides the quantity of energy required per unit output, it does not distinguish between useful energy and the part of the energy that cannot be transformed into physical work. Exergy intensity provides a more meaningful measure of the amount of exergy used per unit of economic output (Figure 15). Exergy intensity (Exergy/GDP) more accurately shows the capacity of the societies to transform exergy into economic output.

Exergy intensity in Mexico was flat from 2003 to 2018. During this time, the economic policy and economic structure were almost identical, reflected in the exergy intensity. In contrast, since China became a member of the World Trade Organization, its exergy intensity fell by half between 2000 and 2008. In 2000, China was the seventh exporter of goods and services and rapidly became number one by 2009; in addition to its annual growth rate (8 % on average), those changes were reflected in the exergy intensity performance. The exergy intensity for Mexico was around 5 MJ/USD, very close to that of the UK's performance.

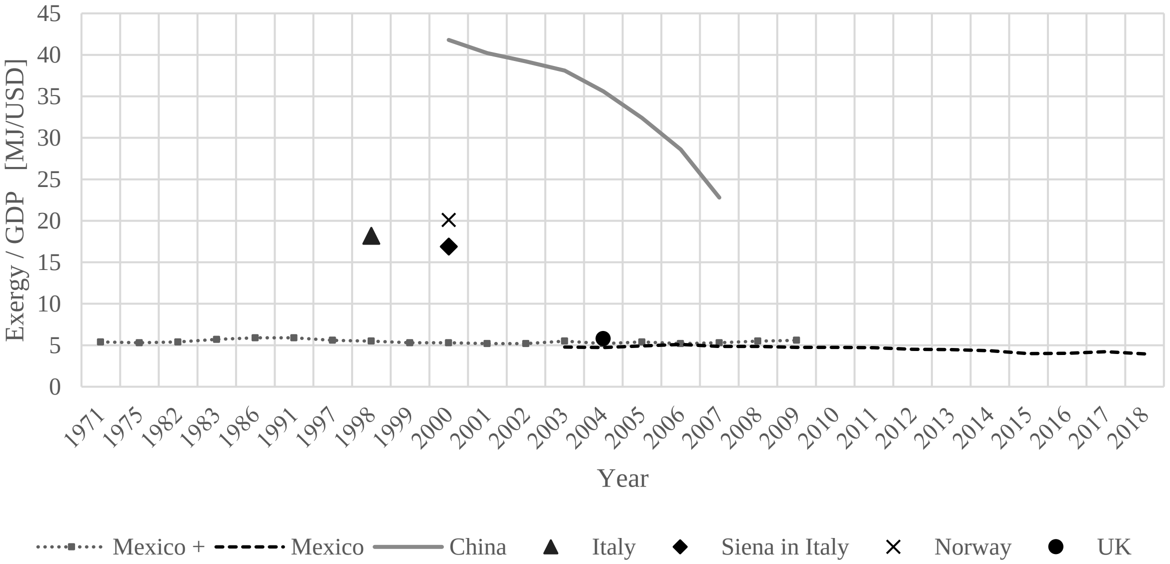


Figure 15. Exergy intensity in various countries over time. Data from China, Italy, the UK, and Norway were taken from Chen et al. [87], and data from Mexico from 1971-2009 (legend "Mexico +") were taken from Guevara et al. [55]. The exergy intensity of Mexico from 2003 to 2018 is our calculation (2010 USD dollars).

Guevara et al. [55] estimated the exergy intensity for Mexico from1971 to 2009 (their results were plotted in Figure 15 with the legend "Mexico +"); however, for these calculations, they used the energy grade function estimated by Serrenho et al. [47] in the Portugal context. Our Exergy intensity results are shown in the same figure as well, with the legend "Mexico". It should be noted that for the case of this work, the exergy factors were calculated considering the compositions of the fuels reported by the Ministry of Energy in Mexico (SENER) each year. That is why some slight discrepancies are observed; therefore, it could be assumed that the results estimated in this research are more precise because they consider the actual chemical compositions used. Despite this, the variations are minor, and a clear trend and continuity can be observed in the estimates.

2.3.4. Exergy used and Exergy destroyed per capita.

Exergy loss and exergy destruction show the resources that society loses and never will get back. Because exergy provides insight into energy dissipated into the environment, some authors have proposed that exergy destruction can be a good measure of the disturbance in ecosystems related to human activities [51], [110], [111]. In Mexico in 2018, 31 GJ were wasted per person, representing 85 MJ / capita per day.

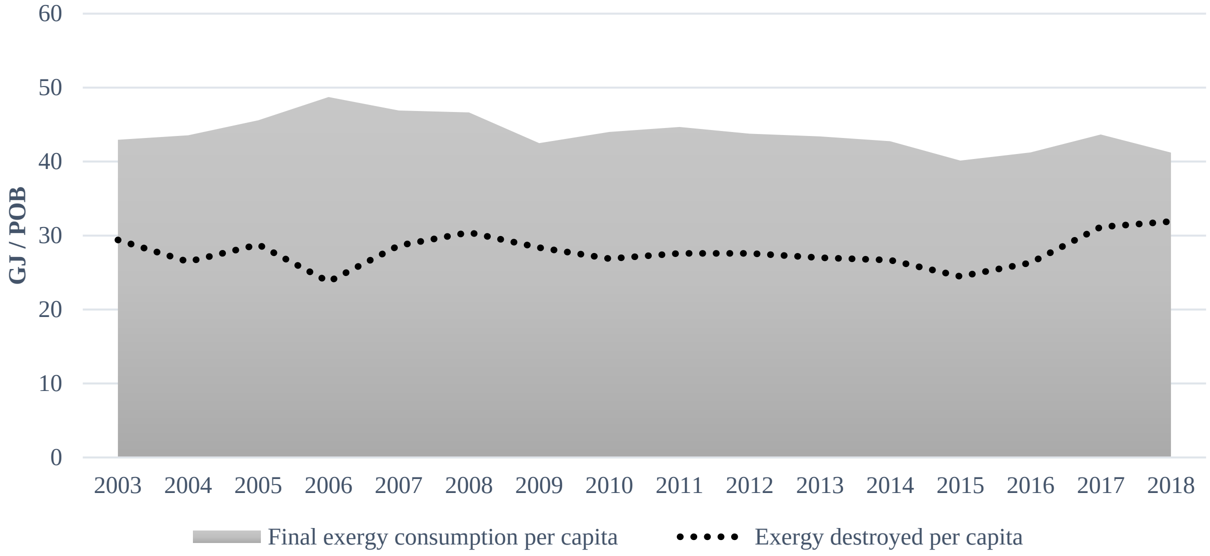


Figure 16. Exergy used and exergy destroyed per capita in Mexico.

Regarding the Exergy destruction per capita and the Exergy destruction per GDP, today, there is no information that they have been previously proposed in other research. The final exergy consumption and the exergy destruction per capita reflect society's exergy consumption and the entropy generated, respectively (Figure 16). However, it should be noticed that a decline in the final exergetic consumption is not necessarily reflected in lower destruction of exergy and vice versa; this is due to the exergetic efficiency. Exergy destruction does not reflect the differences in exergy consumption or destruction due to the income level of individuals in a country. However, it can be used as a measure to contrast the differences across countries or regions.

This work shows the exergy destruction and exergy used per capita in the same graph (Figure 16) because they provide information about the Jevons paradox in the performance of the economies. Jevons's paradox states that when there is an increase in efficiency, an increase in resource consumption is more likely than a decrease. Specifically, the Jevons paradox implies that introducing technologies with greater energy efficiency can ultimately increase the total energy consumption [112] observed in the case of Mexico in 2006 (Figure 16).

Exergy can be considered a production factor. The per-capita exergy input in a social system measures its "operational efficiency" [99], which refers to the average consumption per person within a population. Per capita consumption can differ between wealthy and poor populations. The exergy used in Mexico was 41 GJ per capita in 2018 (Figure 16); this is end-users exergy consumption, and it represents the total amount of exergy that a country uses to satisfy the necessities of all its population.

2.3.5. Entropy increases as an overall environmental impact measure

The following section proposes a new indicator based on entropy that could be visualized to measure the degradation of the environment. It is a proposal that is presented below and is open to discussion.

The exergy analysis can measure the ecosystem disturbance related to human activities [51], [110], [111]. Exergy can measure the resources as inputs for the economic system, and it also can measure the material output. According to Pal (2017), the exergy destroyed in the system is directly proportional to the entropy produced due to the system's irreversibilities. The proportionality constant is the absolute temperature of the environment. The entropy generation can help identify the environmental damage through exergy destruction. This will help to concentrate efforts to act in favor of increasing efficiency and saving resources.

Entropy generated per unit of Gross Domestic Product and entropy generated per capita were calculated. These indicators measure the energy waste emitted into the environment, which has not been considered in the traditional analysis. The Entropy generated was 11.19 kJ/$K in 2003 and 10.46 kJ/$K in 2018 (see Figure 17). The entropy generated increased from 100.35 MJ/popK to 108.8 MJ/popK in 2003 and 2018, respectively.

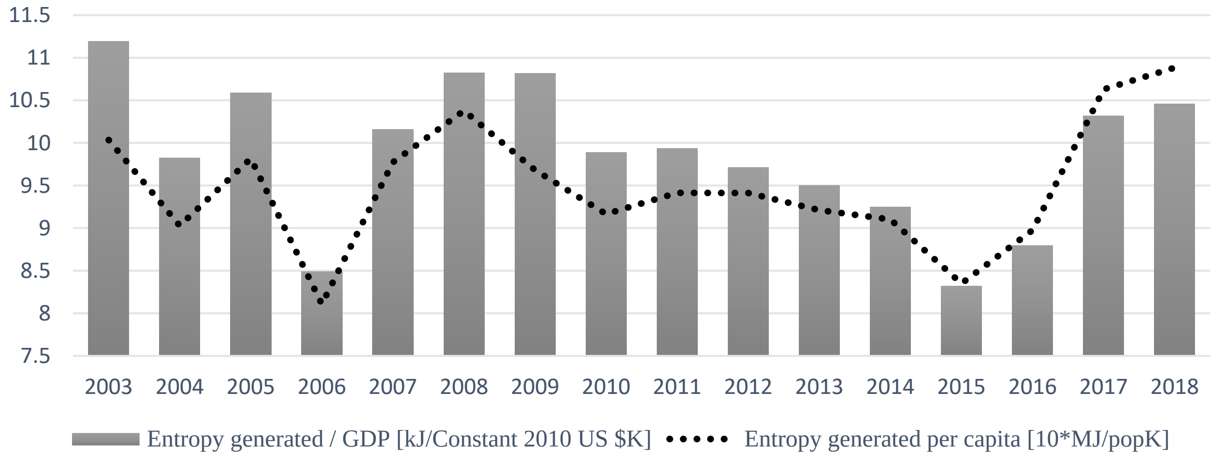


Figure 17. Entropy generated / GDP and Entropy generated per capita in Mexico. The entropy generated per capita series was divided by 10 to plot in the same graph.

Identifying and quantifying the generation of entropy becomes essential for two reasons. First, fossil energy resources are finite, and their fair use is required. Second, while using resources, entropy is generated, which translates into dissipated heat that eventually reaches equilibrium with the environment's temperature; at this point, there is no potential to do work. This waste heat has not been studied seriously and contributes to global warming and climate change. Exergy efficiency and entropy increase would be essential in measuring countries' performance and the world itself. Here is the first practical proposal for measuring entropy generation. This indicator could serve as a basis to measure the overall environmental impact of energy and materials use and inefficiencies for economies, societies, countries, and the world.

2.4. Conclusions

The new approach to incorporating the exergy perspective into national accounting was proposed in this chapter. The methodology proposed in this document can be replicated and applied to analyze other countries. Moreover, to contribute to sustainability analysis, several indicators have been proposed.

Exergy methods can act as a complement to the current energy systems analyzes approach. Moreover, the method and the indicators developed in this research could help to plot energy and public policy in a broad way to meet economic and environmental goals since exergy and their conclusions could be used to determine the taxes and financial penalties applied to polluters because the exergy destroyed correlates with the theoretical work required to undo the environmental damage or clean up [113]–[115].

Chapter 3. Exergy analysis in the industrial sector as an exemplification

3.1 Introduction

This chapter aims to provide an exergy analysis in the industrial sector as an example of how exergy could be used to analyze an economic sector; the exergy analysis was carried out in the beer industry. However, it can be replicated in other industrial branches in Mexico or the world. It can be seen as a complementary tool for implementing energy management programs and diagnoses.

Based on the literature, comprehensive and detailed exergy analysis of an industrial beer has never been carried out before. Therefore, this study aimed to perform a comprehensive exergy analysis of the beer industry in Mexico, including devices and machinery in the beer production lines. Each component of the industry's energy efficiency and exergy destruction rate were determined individually to diagnose the breakthrough points for energy savings. In general, the consequences of applying such analyses could be of interest to plant managers, designers, researchers, and decision-makers worldwide in distinguishing the locations of energy losses to achieve the most cost-effective and eco-benign dairy processing procedures.

3.2. Industry overview

The Gross Domestic Product (GDP) is the sum of the economic value (in money) of all the goods and services of final use generated by a country during a period. A country's economy grows when its GDP increases from one period to another. In Mexico, various economic activities exist to obtain food, consumer products, and goods and thus meet the population's needs. Among them are Fishing and aquaculture activities primaries dedicated to capturing and breeding aquatic species. Mining economic activity is responsible for mineral extraction, exploitation, and use. The industry, which corresponds to the secondary, is the economic activity through which raw materials are transformed into goods and articles consumed or used. Tertiary activities include trade and services [116].

All economic activities consume energy to meet economic goals and produce goods and services. The industry contributes around 30 % of the Mexican GDP, and Mexico City, Nuevo León, and Jalisco are the states with the largest participation [116]. Figure 18 shows the final exergy consumption in Mexico – the industrial exergy consumption grew from 1451 PJ to 1676 PJ in fifteen years. It can be noted that a significant drop in exergy consumption in 2009 can be explained due to the global financial crisis in 2008.

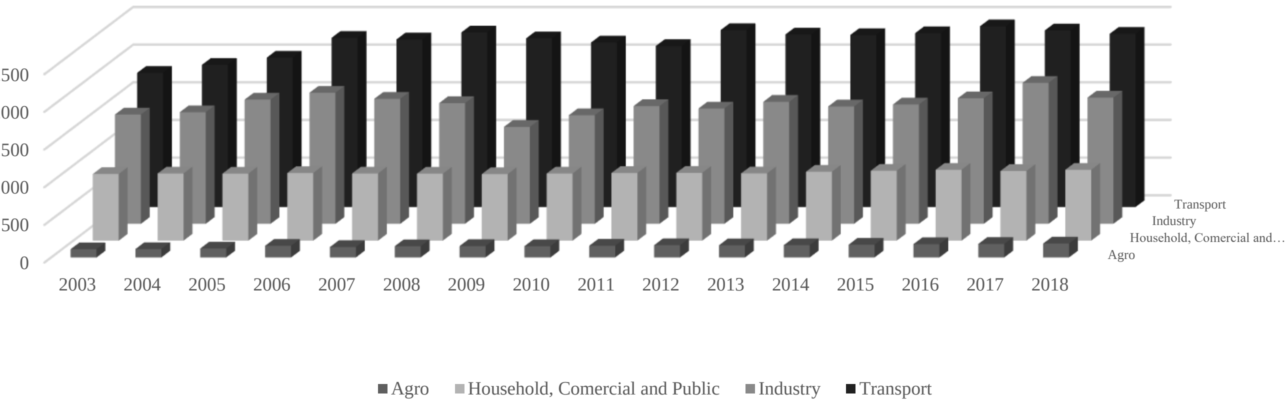


Figure 18. Final exergy consumption in Mexico, in PJ

Including exergy analysis in economics could help to understand the relationship between economic growth and exergy consumption [117], [118]. Exergy consumption is related to the value-added of economic activities; for example, industry value added as a percentage of GDP represented 31.2 % in 2003 and 30.9 % in 2018, these quantities corresponded to 32.8 % and 32.2 % of the total exergy consumption, respectively. This tendency is similar in other economic activities such as agriculture, forestry, and fishing. Table 7 shows the value added to the GDP for several economic sectors and the exergy consumption as a percentage of Mexico's total exergy consumption from 2003 to 2018.

Table 7. Value added as a percentage of GDP and Sector exergy consumption as a percentage of the total exergy consumption.

Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Value added by the industrial sector as a % of GDP	31.2	32.9	32.8	34.2	33.8	34.8	31.9	32.4	33.6	33.8	31.9	31.5	30.0	29.5	30.8	30.9
Industry's exergy consumption as a % of total exergy consumption	32.8	32.5	34.1	33.2	32.4	31.0	26.9	28.7	30.2	29.8	31.4	30.3	32.4	32.8	34.3	32.2
Value added by Agriculture, forestry, and fishing, as a % of GDP	3.4	3.3	3.1	3.1	3.2	3.2	3.2	3.2	3.1	3.2	3.1	3.1	3.2	3.3	3.4	3.4
Agriculture, forestry, and fishing´s exergy consumption as a % of total exergy consumption	2.5	2.4	2.5	2.9	2.7	2.9	3.2	3.0	3.0	3.2	3.1	3.2	3.5	3.5	3.3	3.6

Electricity, natural gas, coal, and coke are the most critical energy carriers to industry, representing 36, 30, 11, and 12 percent of the total industry exergy consumption, respectively (see Figure 19). According to Wall et al. [33], electricity can be transformed 100 % into work. Moreover, electricity is versatile because it can be used in several processes and devices like engines, lighting, heat, etc. Natural gas can also be used as a fuel to produce heat or as a synthesis gas. The versatility, ease of transportation, and available infrastructure are why electricity and natural gas are widely used in the industrial sector.

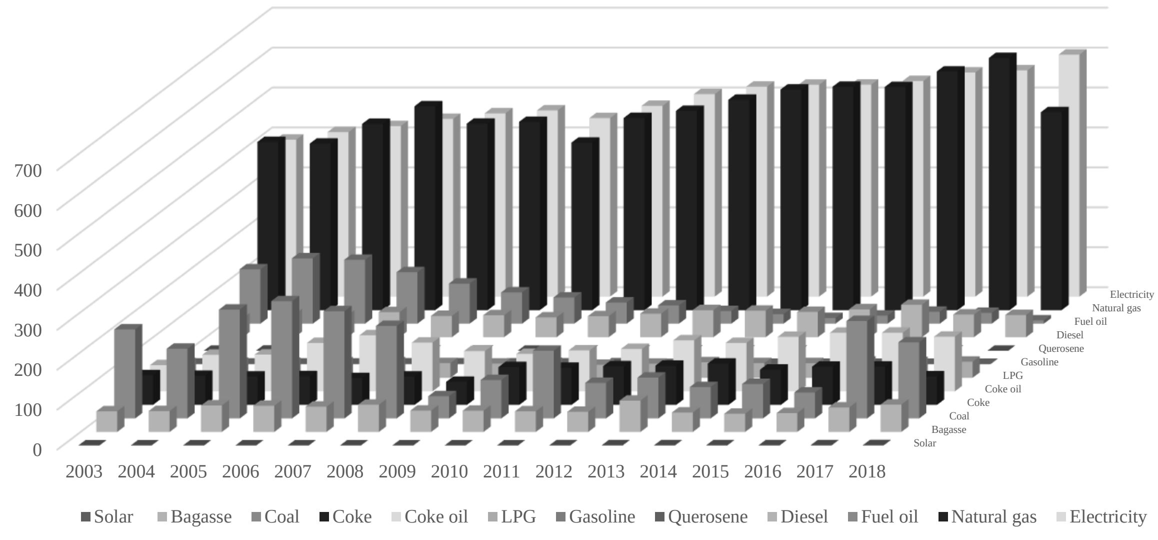


Figure 19. Exergy consumption in the Mexican industrial sector, in PJ.

3.3. Beer Industry

According to Deloitte [119], beer represents 75% of the global market share for alcoholic beverages. The global beer market was valued at $530 billion in 2016, with the world's leading markets being India, China, the United States, Brazil, Russia, Germany, and Mexico. China is the leading beer producer, with 448 million hectoliters (hl) in 2016, followed by the United States with 221 million hectoliters. The total beer production in Mexico was 120 million hl in 2018. Mexico was the fourth beer producer and the first exporter worldwide [119]. To meet beer's production target, the beer industry in Mexico consumed 24.44 PJ of exergy in 2018 (Figure 20).

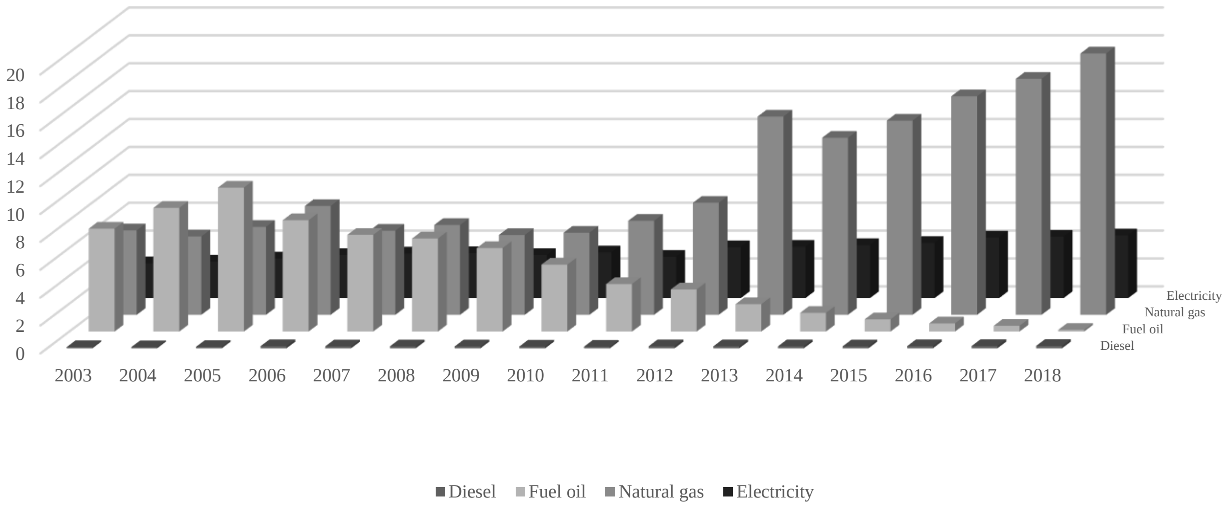


Figure 20. Exergy consumption in Mexico's beer industry, in PJ.

Table 8 shows the energy consumption, the energy grade function, and the exergy consumption by the beer industry in Mexico. It should be noted a drop in fuel oil consumption and a growth in natural gas consumption since 2010.

Table 8. Energy consumption and the exergy factor in the beer industry in Mexico, 2003-2018.

Primary energy consumption by the beer industry																	
Energy carrier	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Unit
Diesel	0.08	0.08	0.09	0.12	0.13	0.14	0.13	0.12	0.11	0.14	0.14	0.14	0.15	0.16	0.17	0.18	PJ
Fuel oil	7.58	7.93	8.6	6.65	7.22	7.12	6.5	5.07	3.64	3.17	2.08	1.4	0.95	0.64	0.44	0.13	PJ
Natural gas	5.79	5.37	6.03	7.46	5.77	6.14	6.07	5.97	7.09	8.41	15.26	13.69	15.16	16.99	18.31	20.33	PJ
Electricity	2.5	2.62	2.84	3.09	3.2	3.23	3.09	3.28	2.96	3.65	3.68	3.8	3.96	4.34	4.4	4.5	PJ
Total	16.35	16.41	18.01	17.9	16.99	17.33	16.5	15.13	14.61	16.18	21.97	19.87	21.1	23.04	24.29	26.16	PJ

Energy grade function																	
Energy carrier	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Average
Diesel	1.056	1.024	1.086	1.303	1.043	0.99	1.035	1.037	1.014	1.043	1.031	1.049	0.936	0.976	0.986	0.972	1.036
Fuel oil	0.973	1.118	1.2	1.201	0.961	0.937	0.921	0.947	0.936	0.953	0.945	0.957	0.922	0.918	0.94	0.942	0.986
Natural gas	1.046	1.046	1.046	1.046	1.046	1.049	0.943	0.986	0.951	0.955	0.932	0.928	0.918	0.922	0.924	0.922	0.979
Electricity	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Primary exergy consumption by the beer industry																
Energy carrier	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Unit
Diesel	0.085	0.082	0.098	0.156	0.136	0.139	0.135	0.124	0.112	0.146	0.144	0.147	0.14	0.156	0.168	0.175	PJ
Fuel oil	7.378	8.867	10.32	7.985	6.936	6.672	5.989	4.799	3.406	3.02	1.965	1.34	0.876	0.587	0.414	0.122	PJ
Natural gas	6.056	5.617	6.307	7.803	6.035	6.439	5.726	5.888	6.746	8.034	14.22	12.7	13.92	15.67	16.93	18.74	PJ
Electricity	2.5	2.62	2.84	3.09	3.2	3.23	3.09	3.28	2.96	3.65	3.68	3.8	3.96	4.34	4.4	4.5	PJ
Total	16.4	17.58	20	19.6	16.89	17.08	15.55	14.68	13.93	15.56	20.73	18.71	19.66	21.55	22.76	24.44	PJ

The beer industry employed 55 thousand direct and 2.5 million indirect people in Mexico. 4.5% of the annual tax income comes from the beer industry, and 1 million points of sale were registered in Mexico by 2017 [119]. Of the total world beer exports, Mexico participated with 21.3%, being the most important beer-exporting country worldwide [120]. The industrial beer sector in the world has been consolidated in such a way that two mega-competitors dominate the market (after the acquisition of SAB Miller by AB InBev in 2016). In Mexico, there is a duopoly in industrial beer production (Table 9). The Herfindahl-Hirschman Index (HHI) is used to determine market competitiveness. An HHI index less than 1,500 is considered a competitive market, an HHI of 1,500 to 2,500 is moderately concentrated, and an HHI of 2,500 or greater is highly concentrated.

Table 9. Mexico's beer market structure, 2018. Source data: [121]–[123].

Index	**Craft Beer**				**Industrial beer**	
	Group A	Group B	Group C	Group D	Group E	Total
Sales hl/branch	0-100	101-500	501-3000	0-3000	+ 3000	0 - ∞
Num of branches	162	34	19	215	2	217
% of branch	75%	16%	9%	99%	1%	100%
Total sales hl/group	3888	8454	52220	64562	119935438	120×10^6
% of the Industry's production	0.003%	0.007%	0.044%	0.054%	99.9%	100%
% of Craft's beer production	6.0%	13.1%	80.9%	100.0%		
Herfindahl Hirschman Index	HHI Craft Beer	349.59			HHI Industrial Beer	5005.25

3.4. Beer production process

Beer production includes several processes. Fermentation is the process by which glucose is converted to ethanol and carbon dioxide. The controlled fermentation of wort produces beer.

The pre-fermentation process includes malt milling, mashing, hops extraction, and wort clarification. When milling is complete, the grist case is emptied into the mash conversion vessel, and purified water at 75 °C is added for mashing. Mashing describes combining malt and purified water to extract the sugars from the malt.

The fermentation stage starts when clarified wort is sent to a large fermentation tank, where the temperature is maintained at 20 °C. In the fermenters, the yeast metabolizes the sugars dissolved in the wort. The primary products are ethanol and carbon dioxide. The fermentation length depends on the beer's desired final alcohol content.

According to Campbell [124], fermentation is expressed chemically as Eq 13. It should be noted that several enzymes and reactions occur anaerobically inside the cells of brewing yeast - behind this simplified chemical reaction is a series of complex biochemical reactions known as the "glycolytic pathway" [124].

$$C_6H_{12}O_6 + 2PO_4^{3-} + 2ADP \rightarrow 2C_2H_5OH + 2CO_2 + 2\ ATP \qquad \text{(Eq. 13)}$$

The post-fermentation stage starts when the beer is moved into bright tanks where it is allowed to condition, and additional flavorings may be added during the aging process. In the bright tanks, additional carbonation may also be added. Once conditioning is completed, the yeast is filtered out, and the beer is either pumped into kegs or to the bottling line. The bottled beer is then generally exposed to a stream of hot water to kill any remaining yeast or microbes and to fix the flavor profile. Figure 21 summarizes the overall beer production process.

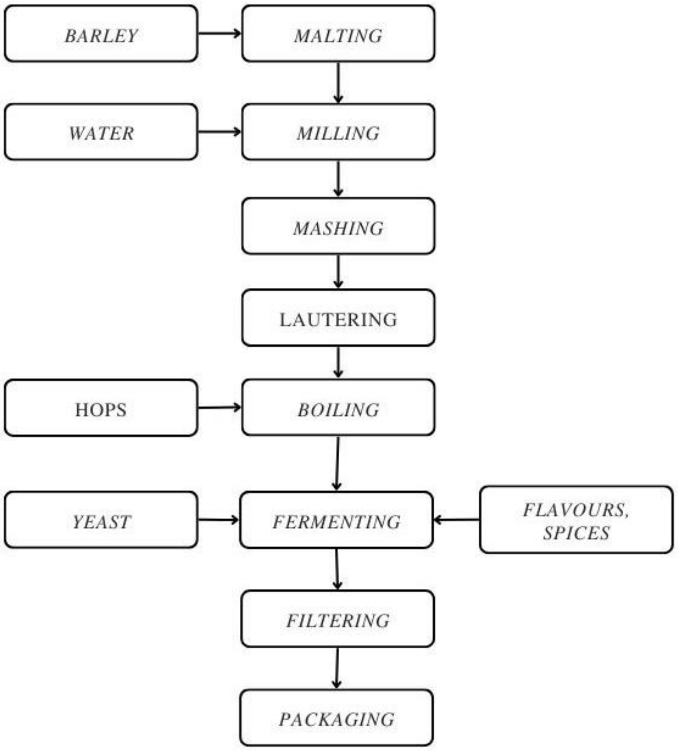


Figure 21. Brewing flowchart

While the brewing process is very well characterized, there are several alternatives to consider in selecting specific methods and equipment. The equipment analyzed in this research were: mills and cereals mills, mixing pads with stirrer and heating, storage tanks, pumps, maceration pans with stirrer and heating, heater kettles with heating, wort cooler, grain washer, fermenter tank, maturation tank, and bottle filling machine (see Figure 22 and Table 13).

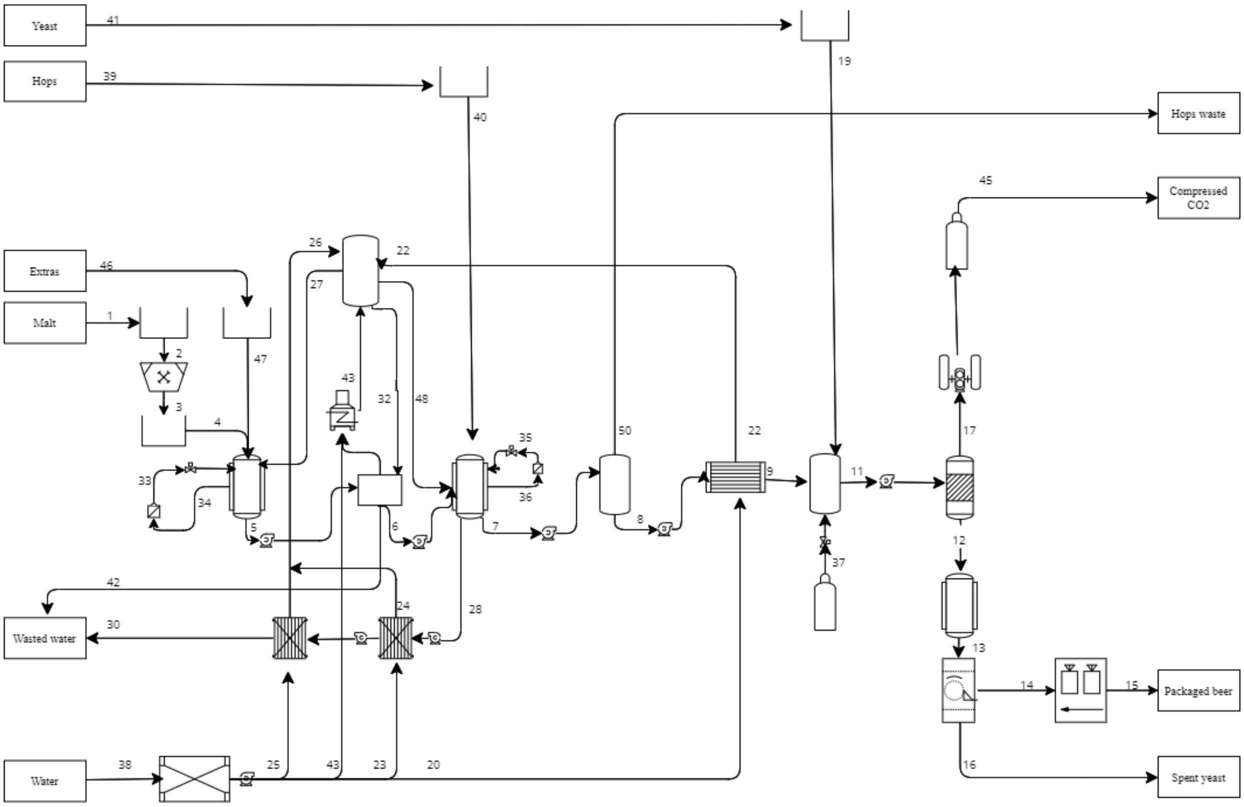


Figure 22. Beer production flow diagram

The assumptions made in the mass and exergy balance were: (1) the whole plant and its components were assumed to be operated in Steady-state condition, (2) the kinetic and potential exergies of various flows were ignored due to their negligible contributions to the total exergy (3) the dead state temperature and pressure were considered as 293.15 K and 101.325 kPa, respectively, (4) The change in the ambient temperature was ignored. (5) we assume homogeneity in the beer production process, (6) We only analyze industrial beer production; this industry has two different types of plants; the first one is the Craft beer plants - there are 215 plants that produce 0.054 % of the output and are in a competitive market. On the other hand, the two branches provide 99 % of the beer production in the country. We analyze the plants that belong to these two big branches (see Table 9) (7). We consider it a homogeneous industry. We know that the plants have different production capacities; however, we consider that the technology is similar. We estimate the average efficiency of the equipment. This work aims to understand and show the exergy consumption in the whole industry, not in a specific plant.

Table 10 shows the mass balance for a year of production of 120 million hl, representing 913 beer tank trucks daily. The mass and exergy consumption data in the whole industry were calculated. The beer production data were taken from: [120], [121], [125].

Table 10. Brewing mass balance

Stream/Number	From	To	Temperature [°C]	Pressure [Atm]	Mass flow rate [Ton/Year]	Malt	Hops	Yeast	Water	CO_2	Alcohol	Air	Waste
1	Malt	V-0	25	1	3388400	3388400	0	0	0	0	0	0	0
2	V-0	M-0	25	1	3388400	3388400	0	0	0	0	0	0	0
3	M-0	V-1	25	1	3388400	3388400	0	0	0	0	0	0	0
4	V-1	V-3	25	1	3388400	3388400	0	0	0	0	0	0	0
5	V-3	V-4	70	1	23041567	3388400	0	0	19653167	0	0	0	0
6	V-4	V-5	70	1	22651193	2846256	0	0	19804937	0	0	0	0
7	V-5	V-6	95	1	21335005	2846256	52725	0	18436024	0	0	0	0
8	V-6	E-3	95	1	12521292	2277005	2085	0	10242202	0	0	0	0
9	E-3	V-8	20	1	12521292	2277005	2085	0	10242202	0	0	0	0
10	V-7/E-3	V-8	20	1	12634785	2277005	2085	113493	10242202	0	0	0	0
11	V-8	R-0	20	1	12662190	2277005	2085	127195	10242202	0	0	13703	0
12	R-0	V-9	20	1	12123323	1126438	2085	149536	10242202	27554	575507	0	0
13	V-9	S-0	10	1	12149536	1126438	2085	149536	10242202	53768	575507	0	0
14	S-0	K-0	10	1	12000000	1126438	2085	0	10242202	53768	575507	0	0
15	K-0	Beer	10	1	12000000	1126438	2085	0	10242202	53768	575507	0	0
16	S-0	Spent Yeast	20	1	149536	0	0	149536	0	0	0	0	0
17	R-0	G-1	20	10	524867	0	0	0	0	524867	0	0	0
18	G-1	V-9	20	10	26065	0	0	0	0	26065	0	0	0
19	V-7	V-8	20	1	113493	0	0	113493	0	0	0	0	0
20	W-0	E-2	25	1	11465452	0	0	0	11465452	0	0	0	0
21	E-2	E-3	10	1	11465452	0	0	0	11465452	0	0	0	0
22	E-3	V-2	85	1	11465452	0	0	0	11465452	0	0	0	0
23	W-0	E-0	25-25	1	18415470	0	0	0	18415470	0	0	0	0
24	E-0	V-2	85	1	18415470	0	0	0	18415470	0	0	0	0
25	W-0	E-1	25-25	1	2219216	0	0	0	2219216	0	0	0	0
26	E-1	V-2	85	1	2219216	0	0	0	2219216	0	0	0	0
27	V-2	V-3	75	1	19653167	0	0	0	19653167	0	0	0	0
28	V-5	E-0	100	1	2048381	0	0	0	2048381	0	0	0	0
29	E-0	E-1	100	1	2048381	0	0	0	2048381	0	0	0	0
30	E-1	Waste	35	1	2048381	0	0	0	2048381	0	0	0	0
31	V-4	F-0	70	1	2710869	542293	0	0	2168576	0	0	0	0
32	V-2	V-4	80	1	18433343	0	0	0	18433343	0	0	0	0
33	B-0	V-3	134	3	291477	0	0	0	291477	0	0	0	0
34	V-3	B-0	134	3	291477	0	0	0	291477	0	0	0	0
35	B-1	V-5	144	4	2059849	0	0	0	2059849	0	0	0	0
36	V-5	B-1	144	4	2059849	0	0	0	2059849	0	0	0	0
37	G-0	V-8	20	10	13703	0	0	0	0	0	0	13703	0
38	Water	W-0	25	1	36597401	0	0	0	36597401	0	0	0	0
39	Hops	V-0	25	1	52725	0	52725	0	0	0	0	0	0
40	V-0	V-5	25	1	52725	0	52725	0	0	0	0	0	0
41	Yeast	V-7	25	1	113493	0	0	113493	0	0	0	0	0
42	V-4	Waste Water	70	1	16112847	0	0	0	16112847	0	0	0	0
43	W-0	F-0	25	1	4497263	0	0	0	4497263	0	0	0	0
44	F-0	V-2	85	1	6665839	0	0	0	6665839	0	0	0	0
45	G-1	CO_2	20	10	498802	0	0	0	0	498802	0	0	0
46	Extras	V-1	25	1	0	0	0	0	0	0	0	0	0
47	V-1	V-3	25	1	0	0	0	0	0	0	0	0	0
48	V-2	V-5	80	1	679467	0	0	0	679467	0	0	0	0
49	F-0	Malt Waste	70	1	542293	0	0	0	0	0	0	0	542293
50	V-6	Hops Waste	95	1	8813712	569251	50640	0	8193821	0	0	0	0

Some of the environmental impacts of beer production are high energy consumption - heating and cooling, high discharge of organic matter, high water consumption, handling of solid waste, air pollution, handling of chemicals, and hazardous waste generation. Figure 23 shows that most brewing exergy consumption was used in heating and cooling.

Processes	**PJ**
Mash conversion vessel	0.41
Hops boil	3.10
Fermenter	0.96
Steam condenser	4.63
Liquor Heater	4.63
Wort cooler	2.83
Spent grain furnace	1.33
Total	17.88

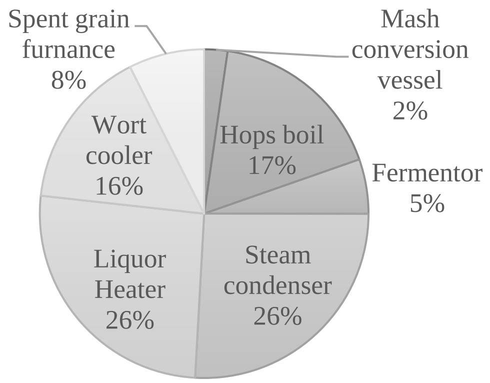


Figure 23. Exergy consumption in the beer production process.

Figure 24 shows the additional exergy consumption in the beer production process. Like other energy-intensive industries, the beer industry is looking for ways to reduce it is energy consumption by discounting the production cost and preventing detrimental environmental impacts; to achieve these goals, incorporating renewable energy resources or improving fossil fuel energy sources is the most usual way to handle them.

Additional processes	**PJ**
Miller	0.16
Mash conversion vessel agitator	0.24
Lauter tun agitator	0.60
Hops boil agitator	0.15
Centrifuge	0.24
Bottling line	0.84
Water purification system	0.30
Pumps	0.53
Total	2.52

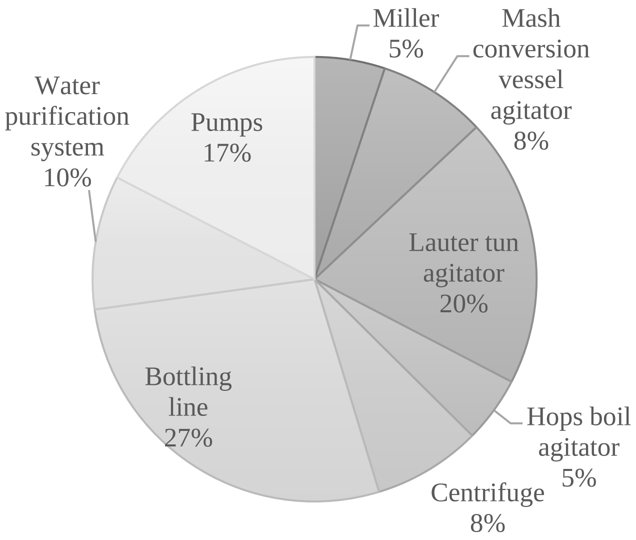


Figure 24. Additional exergy consumption in the beer production process.

3.5. Conclusions

To reduce environmental impacts, engineering tools such as exergy analysis have been extensively applied during the past few decades to analyze and optimize several energy-intensive industries' energetic performance [126]–[131]. The analysis of an industrial branch is essential to analyze exergy consumption. This chapter exemplified an exergy analysis by sectors and branches; its use will be illustrated in the beer industry. It is proposed that these analyzes carried out in a standardized manner and incorporated into the national energy balances could help to enrich the energy point of view to relevant decision makers.

Chapter 4. The challenge: The incorporation of exergy in the national accounting

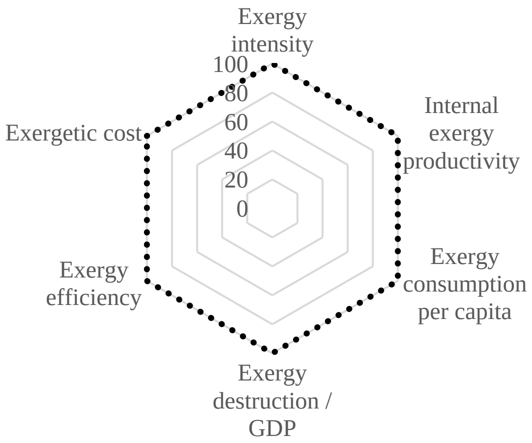
4.1. Introduction

To increase the impact of exergy research, it is necessary to link scientific research with public policy, national budgets, and foreign policy (international agreements). That is why there is a need for a broader consensus among policymakers, scientific experts, and industrial communities. This is especially important when developing more appropriate tools to support decarbonization and energy efficiency strategies is increasingly urgent [37]. This chapter summarizes the critical points about exergy, how to incorporate it into the current national energy balance, and its policy links; it explains how the concept of exergy influences and helps decision-makers. All of the above are within the framework of the Sustainable Development Goals (SDGs) guiding principles.

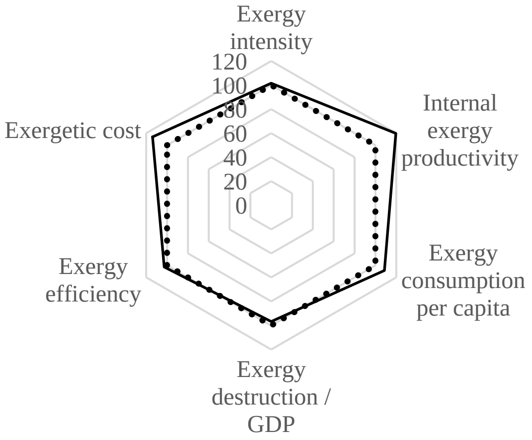
4.2. Sustainability diamond

The exergy analysis can lead to the most efficient use of energy to rethink the energy sector and the economic structure. In this sense, this work provides some new indicators based on exergy conforming to Mexico's sustainability diamond (see Figure 25). The sustainability diamond can work as a theoretical basis for increasing the efficiency of the production factors and reorganizing the energy sectors' structure and their way to satisfy the necessities of the societies to set up less wasteful energy systems in terms of exergy. If this translates into other sectors, it will help to identify inefficiencies and optimize the processes by introducing internal training programs for engineers, plant managers, and industry practitioners in general so that they feel comfortable with implementing exergy methodologies and interpreting exergy metrics [37].

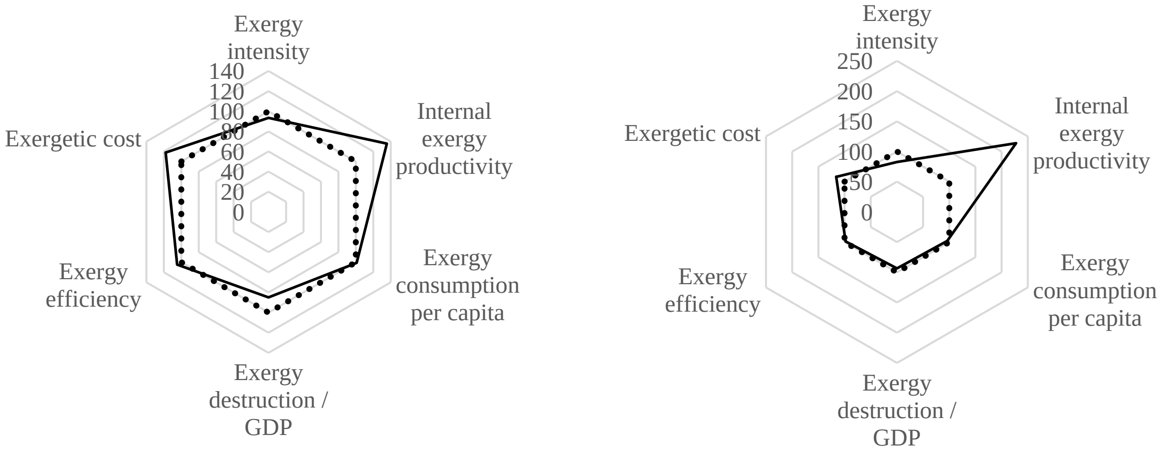
As with energy, multiple indicators can be used to measure exergetic performance. By looking across these indicators (Figure 25), It is possible to get a fuller view of the country’s exergetic performance than looking at only one.



(a) Sustainability diamond of Mexico, 2003



(b) Sustainability diamond of Mexico, 2008



(c) Sustainability diamond of Mexico, 2013 *(d) Sustainability diamond of Mexico, 2018*

Figure 25. Sustainability diamond of Mexico for (a) 2003, (b) 2008, (c) 2013, and (d) 2018, (Where 2003=100).

Figure 25 shows the evolution over time of the six exergy indicators. It would be desirable for the "exergy intensity" indicator to decrease over time, indicating that the economy has become more efficient. The indicator "Internal exergy productivity" reflects the amount of GDP generated by each unit of primary exergy production - This means how much economic wealth was generated in the country by each unit of exergy extracted from the environment on national territory – including both fossil fuels sources but renewable as well but excluding international trade. In Mexico, a considerable increase is observed in internal exergy productivity, from 85 USD/GJ to 195 USD/GJ (from 2003 to 2018). It grew due to the decline in oil production from 2016. This meant changes in the economic structure and public finances to generate financial wealth without exporting oil. Exergy consumption would be desirable to reduce per capita if it is sufficient to meet the population's needs. The Exergy destroyed / GDP would like it to be minimized; this indicates how productive a country has become. It is expected exergy efficiency to increase and the exergetic cost to decrease.

Mexico has great potential to become sustainable, but a successful transformation in the energy sector is required. Mexico's energy system transition must help the country achieve its commitment to curbing climate change [93]. To achieve that, carbon lock-in must be dismantled, improvements in exergy efficiency, new culture to save exergy across all sectors. Exergy analysis could contribute to bringing a unique and complementary point of view. The future law reforms, energy planning, and public policy should be in harmony with the physical provisions and physical restrictions (e.g., exergy destruction, entropy increase, and climate change), the economic context, societal and cultural behaviors, and international treaties. That means energy law reforms and energy transformations should incorporate the local perspective, the physical restrictions, and the global context and trade law's point of view [132], [133]. Mexico was the first developing country to submit a climate action plan [93], [134]; tracking to reach its mitigation goals is necessary.

4.3. Guidelines for National Balances: Exergy key points

The analysis and the results developed in this research contribute to outlining the structure, methodology, and utility of exergy balances. It is a first approach that will allow the elaboration of a straightforward guide that allows the incorporation of exergy concepts and indicators in the national energy balance accounting. Because to increase the impact of exergy studies that support energy policies, it is necessary to link scientific research with public policies. This section proposes integrating the vision of exergy into the national balances. Table 11 shows how to incorporate the exergy perspective into the current national energy balances.

Table 11. Energy balance versus exergy balance

National Balances	Energy balance: Current	Exergy Balance: Proposal
What is?	It shows the **energy** accounting of a country. It is a descriptive instrument that presents the origin and destination of primary and secondary energy sources.	It is a tool that presents the **exergy flows** from the origin and destination of primary and secondary exergy sources. Moreover, it provides the exergy intensity, destruction, and entropy generation accounting.
What is it for?	It is a descriptive instrument that presents the figures of the origin and destination of primary and secondary energy sources during a year. It also incorporates useful information for the analysis of the operation of the **energy sector**, for the design of public policies, and for decision-making.	It is a descriptive instrument that presents the figures of the origin and destination of primary and secondary energy sources during a year. It also incorporates useful information for analyzing the energy system's operation and designing public policies.
Limits:	From energy production to end-user **delivery.**	From energy production to end-user **consumption.**
Objectives:	● Provide basic and comparable information at national and international level for the analysis of the performance of the **energy sector** and the preparation of sector studies. ● Serve as an instrument for planning indicative of the sustainable development of the **energy sector.** ● Publicize the structure of the **energy sector** by its sources and uses it clearly and quantitatively. ● Show the dynamics of energy supply and demand in the current economic context of the country.	● Provide basic and comparable information at national and international level for the analysis of the performance of the **energy sector and all sectors** and the preparation of sector studies. ● Serve as an instrument for planning indicative of the sustainable development of the **energy sector and all sectors.** ● Publicize the structure of **energy sector and all sectors** by its sources and uses clearly and quantitatively. ● Show the dynamics of energy supply and demand in the current economic context of the country.
Units:	Joule [J]	Joule [J]

Mexico's accounting:	It presents the national energy mix and the energy flows broken down by activity and **energy** in the form of diagrams, which show the general structure of the most outstanding accounts of the **National Energy Balance.** The energy sources considered are coal, oil, condensates, natural gas, nuclear energy, hydropower, geoenergy, solar energy, wind energy, sugarcane bagasse, firewood, biogas, coal coke, petroleum coke, liquefied gas, gasoline and naphtha, kerosene, diesel, fuel oil, non-energy products, dry gas; other fuels used in self-generation of electricity such as blast furnace gas and coke gas; in addition to electricity. Additionally, it shows a breakdown of the origin of imports and the destination of exports by country and source.	It will present the national exergy mix, and the exergy flows broken down by activity and by **exergy** in the form of diagrams, which show the general structure of the most outstanding accounts of the **National Exergy Balance**. The exergy sources considered are coal, oil, condensates, natural gas, nuclear energy, hydropower, geoenergy, solar energy, wind energy, sugarcane bagasse, firewood, biogas, coal coke, petroleum coke, liquefied gas, gasoline, and naphtha, kerosene, diesel, fuel oil, non-energy products, dry gas; other fuels used in self-generation of electricity such as blast furnace gas and coke gas; in addition to electricity. Additionally, it shows a breakdown of the origin of imports and the destination of exports by country and source.
Methodology:	It presents the information regarding the supply and demand of energy for a specific geographical area, both nationally and regionally, and is associated with a determined period. It is based on a set of equilibrium relationships that account for the energy that is produced (origin), that which is exchanged with the exterior, that which is transformed, that of own consumption, that which is not used and that which is destined for the different sectors and economic agents (**final destination**).	It will present the information regarding the supply and demand of energy for a specific geographical area, both nationally and regionally, and is associated with a determined period. It is based on a set of equilibrium relationships that account for the energy that is produced (origin), that which is exchanged with the exterior, that which is transformed, that of own consumption, that which is not used and that which is destined for the different sectors and economic agents (**final consumption**).
International accounting:	The methodology used by the IEA is consistent with the International Recommendations for Energy Statistics (IRES), which were adopted by the UN Statistics Commission in 2011 and were based on various consultation processes - the last being the multi-year InterEnerStat consultation, involving at least twenty organizations dealing with energy statistics [3].	The method proposed in this thesis - Chapter 2 and the indicators in section 4.1 can be replicated and applied to analyze other countries. Moreover, the method proposed in Chapter 3 can be replicated around the world in all economic sectors to analyze the final consumption. International organizations can be urged to standardize this methodology. *They can be used to compare exergetic performance across countries. Based on this step-by-step methodology, energy-related indicators. It can therefore fill the same role as standard energy system indicators in informing policy and strategy.*

4.4. Final remarks

The relationships between energy and the economy became important in the 1970s. At that time, the energy-environment relationship did not receive much attention. The issues related to the environment, such as acid rain, air pollution, the deterioration of the ozone layer, global warming, and climate change, took on greater importance in the decade the '80s; since then, attention has been paid to the connection between energy and environment, both in production, transformation, transportation and use which negatively impacted the environment.

Negative externalities are associated with thermal, chemical, and nuclear emissions, all of which are inevitable consequences of processes that meet the needs of society. Conventional energy sources such as fossil fuels are finite and far from meeting the characteristics necessary for sustainable development. At the same time, it is impossible to achieve economic growth without the use of natural resources and the degradation of the environment since they are inherent phenomena in economic processes and life itself.

4.4.1. Exergy and economics

Energy systems contribute to social and economic development and provide human welfare and health, but in recent years may become more important than in the past due to existing limits, so natural energy sources are limited and produce adverse climate impacts [96]. There has been a growing interest in saving energy at the macro level and taking action to reduce energy consumption and emissions of greenhouse gases and improve energy efficiency.

The concept of performance, efficiency, or productivity is central to the production theory. The system and its functional structure must be adapted to efficiently use available resources (capital, labor, raw materials, energy, etc.). Exergy analysis today is implemented far beyond technical analysis; it is also employed in environmental and technical system analysis. It can be used as a sort of “production factor” in economics [99]. It is presently acknowledged that exergy can be considered a production factor proper and that the pro-capita exergy input into a societal system is indeed a measure of its “operational efficiency” [99].

Entering exergy analysis in economics allows us to understand the role of energy in economic growth [117], [118]. Exergy methods are often combined with economics to address financial and economic problems in the industry. This work helps identify optimal systems, processes, and modes of operation in industrial settings. The same methods, however, can be carried out by the government for similar purposes and for extended ones. Certainly, the government can use exergy-economic methods to improve economic performance by providing resources such as funding and expertise to facilitate the adoption of exergy-economic methods [135]. Further, however, the government can use exergy-economic methods to determine how it wishes to affect economic conditions to make certain objectives more likely to be met. For instance, governments can use exergy- economics to determine levels of financial subsidies or taxes, to encourage industry to become more efficient, or to use non-carbon-based energy resources [136].

4.4.2. Exergy and environment

Exergy also has links to environmental issues and impacts that permit exergy methods to be useful tools in efforts to reduce or mitigate environmental impacts. It has been used in global environmental governance because it covers the thermodynamic application to these systems and the material circulation aspects of ecosystem services, including mineral resources that maintain sustainable development [137]. Some have proposed that exergy methods be used to determine the taxes and financial penalties applied to polluters because the exergy of emissions correlates with the theoretical work required to undo the environmental damage or clean up. Other methods for linking exergy and the environment exist that could be useful in formulating government policy. Although work in this area has led to many successes, there appears to be much more opportunity for benefits that will unfold in the future through further research [136], [138].

Exergy analysis is an approach to dealing with energy and environmental issues to achieve sustainability. Some of the information obtained from this approach could supplement the information base for policy support [61], [139]. Exergy allows the integration of economics and thermodynamics; This framework offers fresh perspectives in research and energy policy [140]. Exergy provides a better understanding of the sustainable level of energy systems in the biophysical context [60], [141]. Exergy methods can offer unique insights into possible improvements emphasizing the environment and sustainability. The link between exergy and sustainability development reinforces economics because sustainable development includes economic viability [61].

Exergy provides a better understanding of the sustainable level of energy systems in the biophysical context [60], [141]. Exergy methods could improve environmental and sustainability analysis [61], increase efficiency, and decrease losses and environmental damage [99], [139]. Entering exergy balance in national accounts has become critical [20]–[22], [27] to develop a standard exergy efficiency and exergy auditing methodology and a universal language among practitioners [37].

Integrating exergy criteria in energy planning can be used as a decision tool for addressing the energy transformation systems toward a sustainable 100 % renewable one [142]. Exergy links environmental issues and impacts that permit exergy methods to be useful tools in reducing or mitigating environmental impacts. Exergy can be compared as ratios to other economic or impact variables, such as resource cost or carbon emissions [37]. Governments can use exergy- economics to determine levels of financial subsidies, penalties, or taxes, to encourage industry to become more efficient, or to use non-carbon-based energy resources [136], [143]. Some have proposed that exergy methods be used to determine the taxes and financial penalties applied to polluters because the exergy of emissions correlates with the theoretical work required to undo the environmental damage or clean up [113]–[115].

4.4.3. Exergy in the future

Humanity currently faces various challenges, such as the COVID-19 pandemic, greater climate impacts, and conflicts such as wars, which have repercussions on energy systems, and in turn, on the economic system and society. The COVID-19 pandemic caused aggregate demand to drop, for example, from consuming 100 million barrels of oil per day in 2019 to 70 million barrels per day in April 2020, which caused negative prices. The war between Ukraine and Russia has cut the energy supply (oil and natural gas) and is responsible for world inflation in 2022. Alternatively, the snowfall caused electricity cuts in Texas in 2021, where some people died. Energy systems are critical because they provide the energy to meet broader social necessities.

The ability of Mexico, or any country, to meet broader social and economic goals depends mainly on its ability to use scarce energy resources efficiently. However, misuse of physical resources arises from a poor understanding of concepts such as exergy [113]. That is why we must seek fresh perspectives that help us better understand energy systems. Exergy analysis is a new way of looking at energy systems and extending its use outside academia can positively impact them.

In addition to humanity's current climatic urgency, it is necessary to look at a larger perspective with vision. The environmental impacts are due to the misuse of energy and material resources, or the inefficiencies associated with these processes. That is why the quality of energy and material resources will gain more economic importance for countries and survival for humanity; therefore, it is likely that the term "Exergy" will gain more importance and transcend the academy towards public opinion and decision-making.

Secondly, energy and natural resources are finite, and their misuse generates pollution. Ultimately, inefficiencies and waste of resources translate into entropy generation that harms the planet. For this reason, it becomes essential to quantify with greater precision the performance of economies and the performance of all production processes. That is why the indicators proposed here as "Entropy generation," at a macro level proposed for the first time in this work, can be a guide or a basis for measuring and comparing the efficiency of the performance of economies, societies, countries, or planets. This indicator or related indicators will likely become more critical in the future.

The awareness of exergy can arise from education and media [144]. Bilgen and Sarikaya [61] point out the need to understand the linkages between exergy and economics, environment, ecology, and sustainable development. Herrmann-Pillath [140] considers the necessity to consider individuals and markets as part of an ecological system. Moreover, the development of internal training programs for engineers, plant managers, and general industry practitioners so they are comfortable with implementing exergy methodologies and interpreting exergy metrics [37] and the development of standard exergy efficiency and exergy auditing methodology for industry practitioners is endorsed by international standardization bodies so that there is a universal language among practitioners - like with Life Cycle Assessment today [37]. Education policies that support the inclusion of exergy in relevant curricula at all appropriate education levels should be considered.

4.5. Conclusions

Exergy analysis is an approach to dealing with energy and environmental issues to achieve sustainability. Some of the information obtained from this approach could supplement the information needed for policy support. Policymakers need to acknowledge the importance and utility of the exergy concept due to its several linkages between disciplines, i.e., economics, environment, ecology, and sustainable development [61], [139], to appreciate the exergy concept and its ties to these concerns to incorporate into public policy. This chapter integrates the exergy perspective into national and international policy.

Chapter 5. General conclusions

This thesis presents a replicable, step-by-step approach to characterizing the exergy characteristics of national economies. Based on this methodology, it proposes new indicators, comparable to standard energy-related indicators, to incorporate exergy into the analysis and discussion of national systems. It applies this methodology and indicators to characterize the Mexican energy sector and, when possible, we compare them with other countries.

The sustainability diamond introduced in this thesis can serve as a theoretical basis for identifying critical areas for policy action to increase efficiency. The sustainability diamond can work as a theoretical basis for analyzing the energy systems and their way to satisfy the necessities of the societies because it will help to identify inefficiencies and optimize economic sectors and their processes overtime. The sustainability diamond shows the evolution over time of the six exergy indicators: The "exergy intensity" indicator expected to decrease over time, indicating that the economy has become more efficient. The indicator "Internal exergy productivity" reflects the amount of GDP generated by each unit of primary exergy production. In Mexico it grew due to the decline in oil production from 2016. Exergy consumption would be desirable to reduce per capita if it is sufficient to meet the population's needs. The Exergy destroyed / GDP would like it to be minimized; this indicates how productive a country has become. It is expected exergy efficiency to increase and the exergetic cost to decrease.

The role of exergy in energy systems could have a greater importance if exergy analyzes could be scaled from the traditional analyzes – usually done to analyze devices and machines towards the energy sectors of the countries. And to the national energy sector itself, given that the development of exergy analysis methodologies in the last thirty years has not been able to break their limitations of use only in the academic sector and in applications for processes and machines.

Therefore, this work contributes to helping exergy analysis scale to macro and planning levels, and at the same time, they can be helpful beyond academic issues and could reach the role of analyzing national energy systems. It is a conclusion, desire, or feeling of the exergy community.

While the value of exergy-based analysis is clear, obstacles and issues remain before it can become standard practice for informing energy-related decisions. For one, the concept of exergy is not well understood by decision-makers and the public. This means that the concepts in this document will not be taken up quickly by those that might most benefit from them. However, we believe clear communication – without technical jargon – can make these concepts digestible to a broader audience. In addition to communication issues, the methods for calculation exergy are not mainstream. Exergy analysis also requires additional information beyond that needed for energy analysis. This means moving to an exergy perspective would require disseminating new methodologies, such as the methodology in this thesis, and collecting and synthesizing the data necessary for exergy analysis.

Exergy analysis also helps to achieve a Circular economy framework that has to be baked into the energy transition and sustainability by design to ensure the world has a sustainable energy supply and raw materials. In addition, Exergy destruction and entropy increase indicators help the circular economy perspective to find the energy and raw material losses. This is one of the gaps in circular economy research nowadays.

In Mexico, the Mexican Department of Energy (SENER) has been using energy indicators to understand the performance of the Mexican energy sector, its relationship with the economic sectors, and the opportunities for increased efficiency.

The average energy efficiency in the Mexican energy sector was 79% from 2003 to 2018. In contrast, the exergy efficiency for the same period was 63%. In other words, the exergy perspective indicates a more significant opportunity to improve the efficiency of the Mexican energy system than might be envisioned purely from an energy accounting perspective.

Mexico experienced a drop in primary exergy production from 10,759 PJ in 2003 to 6,714 PJ in 2018. This drop in exergy production is mainly due to a reduction in oil production. Final exergy consumption increased from 4,218 PJ in 2003 to 5,092 PJ in 2018. The economic growth in Mexico can largely explain this increase.

Exergy intensity shows the capacity of the societies to transform exergy into economic output. The exergy intensity for Mexico was around 5 MJ/USD, very close to that of the UK's performance.

The "internal exergy productivity" shows how much economic wealth was generated in the country by each unit of exergy extracted from the environment. In Mexico, a considerable increase is observed in the internal exergy productivity, from 85 USD/GJ to 195 USD/GJ (from 2003 to 2018). This meant changes in the economic structure and public finances to generate financial wealth. - This indicates how much economic wealth was generated in the country by each unit of exergy extracted from the environment on national territory – including both fossil fuels sources but renewable as well but excluding international trade; like "energy intensity" but with the exergy analysis perspective and only local energy resources are included here.

A drop in exergy consumption is not necessarily reflected in lower destruction of exergy and vice versa; this is due to the exergy efficiency because of Jevons's paradox. It states that as technological improvement increases the efficiency with which a resource is used, an increase in the consumption of that resource is more likely than a decrease, as happened to Mexico in 2006.

Each exergy loss or destruction represents an economic loss; in Mexico in 2018, 31 GJ of exergy were wasted per person, representing 85 MJ / capita per day. Indeed, the quantity of exergy destruction is more significant than the total export amount. If we compare the economic value of Mexico´s exports, exergy destruction could represent 2.9 % of GDP.

Mexico has a strong dependency on fossil fuels (92 % of the total primary exergy production) and exergy destruction (30 GJ/capita per year) implies a severe lack of sustainability in Mexico. However, Mexico's energy system has greater potential to become sustainable by incorporating renewables and changing the current trend in exergy supply.

These challenges notwithstanding, more information and more insights mean better decisions. The methodology and analysis in this thesis provide more information and insights that help guide sustainability decisions in Mexico and beyond.

Like any methodology aggregating diverse types of data, the research in this thesis has limitations. One important methodological limitation is that the calculation of the chemical exergy is based on average composition. The specific exergy will depend on the chemical composition of the fuels and will differ in each region and over time. This work assumes a homogeneity of the fuels - we are assuming average composition based on the most current data published by the SENER. In addition, while the methodology proposed in this document can be replicated and applied to analyze other countries, data may prove an issue. The information was based on the method indicated in the World Energy Balance Database from the International Energy Agency. Other researchers who would like to replicate this methodology must ensure that their data information follows the guidelines; otherwise, adjust the data structure. The quality of the data also plays a critical role. This work used data from official information sources in Mexico. The quality of our results depends heavily on this data.

In addition to humanity's current climatic urgency, it is necessary to look at the long run with the vision. The environmental impacts are due to the misuse of energy and material resources, or the inefficiencies associated with these processes. That is why the quality of energy and material resources will gain more economic importance for countries and survival for humanity; therefore, it is likely that the term "Exergy" will gain more importance and transcend the academy towards public opinion and decision-making.

Secondly, energy and natural resources are finite, and their misuse generates pollution. Ultimately, inefficiencies and waste of resources translate into entropy generation that harms the planet. For this reason, it becomes essential to quantify with greater precision the performance of economies and the performance of all production processes. That is why the indicators proposed here as "Entropy generated," at a macro level proposed for the first time in this work, can be a guide or a basis for measuring and comparing the efficiency of the performance of economies, societies, countries, or planets. This indicator or related indicators will likely become more critical in the future.

There are several potential avenues to build on or extend the work in this thesis. First, this thesis has taken a national perspective. Future work might use the results here to identify critical areas for sectoral efficiency gains and then apply the methodology to carry out sectoral and sub-sectoral analyzes that can draw out targeted strategies. Second, it would be helpful to codify the methods in this thesis into software that would ease replication. Third, extending this replicable methodology to other countries would provide a basis for international comparisons. Finally, and building on the previous opportunities, we point out the need to prepare a World Exergy Balance to estimate the exergy destruction in the World. *This work contributes to migrating the exergy approach from engineering devices to help assess national energy systems, countries, regions, and industrial sectors.*

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Annex

Table 12. Flows and processes that conform to the National Exergy Balance.

F1	Primary exergy production	F26	Total final consumption	F51	Beer Industry exergy consumption
F2	Total primary exergy supply	F27	Non-energy consumption	F52	Building industry exergy consumption
F3	Primary exergy imports	F28	Final energy consumption	F53	Soft drink industry exergy consumption
F4	Variations of Primary exergy stocks	F29	Transportation sector energy consumption	F54	Automotive industry exergy consumption
F5	Domestic exergy supply	F30	Household, commercial, and public sectors' consumption	F55	Rubber industry exergy consumption
F6	Primary exergy exports	F31	Industrial sector exergy consumption	F56	Fertilizer industry exergy consumption
F7	Exergy loss	F32	Agricultural Sector Energy Consumption	F57	Tobacco industry exergy consumption
F8	Primary energy inputs in transformation centers	F33	Non-energy use (Petrochemical industry)	F58	Exergy Consumption (other branches)
F9	Primary energy losses in transformation	F34	non-energy use (other branches)	Processes:	
F10	Recirculation and statistical difference	F35	Land transport exergy consumption		
F11	Own exergy consumption in primary conversion process	F36	Air transport exergy consumption	P1	Primary exergy imports
F12	Interproduct transfers	F37	Sea transport exergy consumption	P2	Primary exergy exports
F13	Final primary consumption	F38	Rail transport exergy consumption	P3	Primary exergy production
F14	Secondary exergy production	F39	Electric transport exergy consumption	P4	Transformation
F15	Secondary exergy losses in transformation	F40	Household sector exergy consumption	P5	Secondary exergy imports
F16	Total secondary exergy supply	F41	Commercial sector exergy consumption	P6	Secondary exergy exports
F17	Secondary exergy imports	F42	Public sector exergy consumption	P7	Second transformation center
F18	Variations of Secondary Energy Stocks	F43	Iron and steel industry exergy consumption	P8	Transfer node energy
F19	Secondary exergy supply	F44	Cement industry exergy consumption	P9	Transfer node energy
F20	Secondary exergy exports	F45	PEMEX's exergy consumption	P10	Distribution
F21	Final secondary exergy consumption	F46	Chemical industry exergy consumption	P11	Transfer node energy
F22	Fuels for generating electricity	F47	Sugar industry exergy consumption	P12	Transportation exergy consumption
F23	Own exergy consumption in secondary conversion	F48	Mining industry exergy consumption	P13	Households, commercial and public sectors exergy consumption.
F24	Secondary exergy losses	F49	Pulp and paper industry exergy consumption	P14	Industrial sector exergy consumption
F25	Recirculation and statistical difference	F50	Glass industry exergy consumption	P15	Human Environmental Interactions

Table 13. Detailed equipment list

Unit	Number	Conditions	Function
Boiler	B-0	1 atm, 130 °C	Supply mash conversion vessel steam jackets
Boiler	B-1	4 atm, 145 °C	Supply hops boil steam jackets
Plate and Frame heat exchanger	E-0	1 atm	Condense steam from hops boil
Plate and Frame heat exchanger	E-1	1 atm	Cool hops boil steam condensate
Chiller	E-2	1 atm	Supply chilled water to wort cooler
Wort cooler	E-3	1 atm	Cool wort stream exiting whirlpool
Furnace	F-0	1 atm	Combust spent grain, heat water
Bottling line	K-0		Package final product
Roller mill	M-0		Grind malt into grist
Pump	P-X		Move process liquids
Fermenter	R-0	1 atm, 20°C	Maintain proper environment for yeast cells
Centrifuge	S-0		Separate yeast from beer
Storage vessel	V-0		Store malt
Storage vessel	V-1	1 atm, 25 °C	Store grist
Storage vessel	V-2	1 atm, 85°C	Store purified water
Storage vessel	V-10		Store hops
Storage vessel	V-11		Store extras
Process vessel	V-3	1 atm, 70°C	Agitate mash mixture to extract sugars
Process vessel	V-4	1 atm, 70°C	Drain wort from mash
Process vessel	V-5	1 atm, 100°C	Heat wort to extract hops
Process vessel	V-6	1 atm, 95°C	Separate spent hops form wort
Process vessel	V-9	1 atm, 10°C	Condition beer

Nomenclature and acronyms

$\mathbf{A}$	Incidence matrix
$A*$	Ash
AES	Another energy system
B	Exergy
b	Specific exergy
B*	Exergetic cost
BAU	Business As Usual
Bd	Exergy destruction
C	Carbon
E	Energy
EU	End users
F_i	Flow of exergy
GHG	Greenhouse Gas
H	Enthalpy
H^*	Hydrogen
HHV	Higher heating value
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
m	Mass
N	Nitrogen
NBB	National Exergy Balance
NEB	National Energy Balance
O	Oxygen
PEMEX	Petróleos Mexicanos / State oil company
P_i	Energy sector processes
PJ	Peta Joules
Pop	Population
R	Gas constant
S	Entropy
s	Specific entropy
$S*$	Sulfur
SENER	Secretaría de Energía / Department of Energy of Mexico
SLCFs	Short-Lived Climate Forcers
T	Temperature
T_0	Temperature of the reference environment
x_i	Molar fraction
γ	Energy grade function or Exergy factor
ρ	density

Figures list

Tables list

Equations list