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Exergy analysis of the energy consumption in the Colombian energy mix: An insight from its economic sectors and energy resources

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ABSTRACT

In this paper, the exergy analysis of the performance of the resources consumption in the Colombian energy mix is developed for the years 1975, 1993, 2012 and 2016, based on actual data measured by the Colombian Planning Office of Mining and Energy (UPME), typical exergy performance data of industrial processes a well as specific energy conversion yields for productive activities of the Colombian energy mix. Differently from the existent assessment methodology of the Latin American Energy Organization (OLADE), in this work, a methodology based on the concept of exergy is used to assess the performance of the exergy consumption in each economic sector, without the need for differentiating between primary and secondary resources. The exergy performance of the utilization of the various energy resources through the different economic sectors is represented via Grassmann diagrams from two points of view, namely representing the exergy losses by energy resource and determining the exergy losses by economic sector. The first approach focuses on the study of how the resources are used in the Colombian energy mix, whereas the latter one focuses on how efficient the Colombian economic sectors perform. As a result, a slight increasing trend of the evolution of the overall exergy efficiency of the energy consumption in the Colombian energy sectors can be evidenced. These results prove to be useful in identifying the actual bottlenecks and forecast the future shortcomings that the planning offices and economic decision-makers will face in the scenario of a newly industrializing country with a growing and energy demanding population.

Keywords:

Exergy;
Efficiency;
Energy Sector;
Economic activity;

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1. Introduction

Since the industrial revolution, societies have increased their energy demand in an exponential way [1], rendering the efficient utilization of energy resources a fundamental issue, especially due to the economic and environmental problems associated with its misuse. Thus, in order to use the energy resources more efficiently, firstly, the different flows and energy transformations involved must be clearly determined. According to the First Law of Thermodynamics, energy is rather a conservative magnitude and, as such, it is neither possible to destroy it nor to create it, being only possible to transform it from one form into another [2]. On the other hand, the second law of thermodynamics states that although energy cannot be either created or destroyed, its quality may be actually degraded [3]. Thus, in order to perform a thorough energy conversion analysis, the restrictions imposed by the Second Law of Thermody

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Nomenclature

Greek symbols

ϕ	ratios of the standard chemical exergy to the lower heating value (LHV) (adim.)
η	efficiency (%)

Latin Symbols

B	exergy (PJ)
C	carbon mass fraction in the substance (% mass)
H	hydrogen mass fraction in the substance (% mass)
LHV	lower heating value (MJ/kg)
m_r	mass flow of the substance considered as material or fuel input resource (kg/s)
N	nitrogen mass fraction in the substance (% mass)
N_C	number of carbon atoms
O	oxygen mass fraction in the substance (% mass)
S	sulfur mass fraction in the substance (% mass)

namics must be born in mind, leading to the concept of exergy. Exergy is defined as the maximum work that can be obtained when a quantity of matter is led to the state of thermo-mechanical and chemical equilibrium with the environment, involving only reversible interactions with the components thereof, in order to produce the same components of the environment [4]. For this reason, this magnitude is also known as *maximum potential work* of a substance or a flow when it is defined the environment in which the system is contained. It is important to notice that, unlike the energy, the exergy is not subject to a law of conservation, since the irreversibility inherent to the real processes destroys at least part of this energy. Thus, in light of the irreversible nature of the real processes, the exergy concept is more appropriate to evaluate the behaviour of the energy systems, as it combines the law of conservation of energy with the concept of entropy generation. Thus, regardless the classification of the energy resources, namely a substance (e.g. fuel, wind, or waterfall) or exergy flow (i.e. heat flow rate or power), the performance of the assessment of any energy system, industrial plant or even an economic activity can be rationally achieved. For this reason, exergy efficiency represents a valuable indicator that quantifies the fraction of the total energy consumed in any system that can be potentially transformed into *useful work.*

1.1. Scope and Structure

One of the main drawbacks of the dominant economic model consists of neglecting the limitations that physical principles, such as the Second Law of the Thermodynamics, impose on the productive systems. Traditionally, two misconceptions have misled most of the economic development models. First, it has been assumed that the natural resources available in the biosphere are free. Even worse, in many cases it has been considered that those resources are unlimited [5]. Meanwhile, in most of the developing countries, politicians and specialists struggle for adapting other economic development models based on the experiences of radically different societies to their own scenario. Not to mention that biased and uncommitted governments seldom guarantee the continuity of the planning policies of the previous governments, which keeps societies from structuring successful exergy planning scenarios lasting in time. Even member countries of the Organisation for Economic Co-operation and Development (OECD), criteria are strongly based on the economic features in lieu of the thermodynamic efficiency criterion as for some strategic decision-makings [6].

Thus, not even the advantages linked to the exergy assessment of the entire economic sectors or the concerns about climate change and the depletion of the natural resources have been able so far to persuade the governmental and planning institutions to challenge the dominating economic paradigm. Only few scholars have embraced the Second Law of the Thermodynamics and the concept of *irreversibility* for assessing the *sustainability* of the economic processes. Among the most important contributions towards the integration of the concept of entropy to the economy modelling is the work of the economist Nicholas Georgescu-Roegen (1971) [7]. According to his revolutionary work, any production activity is, essentially, a process of transformation of matter and energy that speeds up the eventual universal *heat death*, but locally on earth. In this way, the irreversible nature of the economic processes explains the growing scarcity of the natural resources and the increasing rate of production of nonrecoverable disposal of residues, aggravated by the irremediable energy degradation provoked at each recycling step. In other words, the dominating economic paradigm seemingly fail to take into account the exhaustion of mineral resources at the input end, and the building up of waste and pollution at the output end. Accordingly, the issue of policies and the decision-making in the current global economic scenario demand a revisited insight that takes into account the irreversibility of the industrial processes and the search for the efficiency improvement as the key elements of the human endeavours. Thus, it is at this point in which the exergy concept becomes as an indicator that allows objectivizing a political discussion into a more technical and quantifiable procedure [8].

Among the first academic approaches on the large-scale exergy analysis is the work of Reistad [9], who studied the use of energy resources in the United States in 1970. Similarly, Utlu et al. [10] and Rosen [11] carried out a comparative exergy and energy analysis of the energy mix of Turkey and Canada, respectively. Despite their relevance, these works were based on very shorts intervals of time, thus making difficult the observation of the evolution of the use of the energy resources over a representative timeframe. The study of the evolution of the energy mix over longer periods has been considered in the works of Hammond et al. [12], and Bühler et al. [13] and [14], based on the energy analyses in the United Kingdom (1965-1995), the Danish industry sector (2006-2012), and the industrial sector in South Africa (1994-2003), respectively. Moreover, Jadhao et al. [15] studied the evolution of the Indian energy system during four decades and concluded that India needs to improve its efficiency at a faster rate than that of more industrialized countries in order to compensate for the negative effects of the rapid population and economic growth. In addition, more recently Gong et al. [16] performed an exergy analysis of the Swedish energy system in which the transportation sector reportedly contributes the most towards the non-renewable energy consumption of the national energy mix. According to the previous works, exergy analysis can be used as a decision-making tool for planning public energy policies of a country. One of the main objectives for carrying out the exergy analysis of a country is to calculate its exergy efficiency and elaborate the representative exergy flow diagrams (Grassmann diagrams), which show the exergy flows distribution from the extraction of the resources up to the final consumption, taking into account all the intermediate processes and exergy losses. For instance, in the works of Ertesvag [17], Wall et al. [18], and Wall [19], the exergy flow diagrams of Norway, Italy and Japan, respectively, have been reported. Meanwhile, the time series analysis of the fossil energy resources consumption in three developing societies has been presented by Kwakwa et al [20]. The authors studied the determinants of the sharp increase in the demand of fossils fuels for three Sub-Saharan African countries (Ghana, Kenya and South Africa). Other African analyses dealt with the climate-resilient and low-carbon power supply scenario for Rwanda [21], in which the evolution of Rwanda's electricity demand towards 2050 is adopted for developing a power supply scenario that considers impacts of climate change on the country's hydropower generation. Finally, a review of the energy economy in Brazil and Portugal, two countries which are both characterised by high utilisation of renewable energy resources, explained how the discrepancies between the two renewable energy mixes lead to slight differences in the performance of the electricity generation and end-use, along with the socio-economic aspects associated [22].

Notwithstanding, the respective exergy flow diagrams of the energy consumption in the Colombian energy mix have not been reported so far. Thus, in this work, actual data on the energy consumption of each energy resource and economic sector over the time reported by the Colombian Planning Office of Mining and Energy (UPME) is used to perform an analysis of the energy consumption in the exergy mix of the Colombian energy sectors over the years 1975-2016 by using the Grassmann diagrams. To this end, two perspectives are considered; the first one comprises the quantification of the irreversibility associated with the consumption of each resource (or equivalently, the *exergy efficiency by resource utilization*). The second one focuses on the estimation of the irreversibility associated with each economic sector (namely, the *exergy efficiency by economic sector*). From the analysis of the Grassmann diagrams, the historical events that led to the changes in the use of the energy resources over the time are also analysed. In this way, this paper examines the evolution of the Colombian exergy mix over the time by showing the exergy flows involved in the different economic sectors and concludes with the calculation of the overall exergy efficiency of the country. The relevance of this work lies in three novelty. Firstly, the Grassmann diagrams of the energy consumption in the Colombian energy mix, based on real data gathered over 1975 and 2016 by credited national energy institutes and other sources found in the literature are built. Secondly, a novel methodology based on the exergy analysis, differently from the OLADE's energy-based approach, is proposed, so that the need for differentiating between the nature of the energy resources is not anymore required. Since the exergy concept is used, the energy degradation in the Colombian economic sectors is automatically accounted for. Last but not least, the relationship between the use of the resources and the historical events that led to the changes of the energy mix of the country is briefly discussed. Preliminary results of this manuscript have been presented in the 31th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2018, in Guimaraes, Portugal, in June 17th – 22nd, 2018.

2. Methodology

The methodology used is schematized in the Fig. 1. As it can be seen, the initial steps comprise the data collection, systematization and adaptation, relevant for the periods under study (1975-2016). An initial benchmarking process allows not only for determining the completeness of the available information for industrial processes and economic sectors around the world, but also to determine whether those values could be adopted for similar process or productive sectors in the Colombian electricity mix. Other important data gathered from open literature includes the thermophysical characteristics of the energy resources that allow for the chemical exergy calculation and exergy balances.

The Colombian Energy Balance (BECO, in Spanish) in which stems the data on energy consumption is based on the actual data gathered, statistically processed, verified and published by the UPME [23]. The BECO relies on the identification of four main components, namely the energy resources, the energy conversion systems, end-use systems as well as other processes non-classifiable into the main economic activities. Thus, BECO methodology starts by identifying the source of energy in the form of primary energy resource, which is subsequently transformed by a defined set of energy conversion systems (a transformation process) into a secondary source of energy, which is in turn consumed by an economic sector. The intermediate energy conversion processes of primary resources to produce secondary energy resources are performed so that the value-added products can be more easily handled or more efficiently converted into other forms of energy. Furthermore, the BECO determines the direct consumption or end-use of such primary and secondary energy resources between 1975 and 2012. The reported balances presented by the UPME contain the energy losses, which facilitates the calculation of the energy yields for each economic sector, whereas this information can be used to extrapolate the losses in the future years. Next, the exergy balances for each energy resource by each economic sector (namely, residential, commercial and public, industry, transportation, agriculture, mining, and construction sectors) can be calculated by using two ways: By calculating the available exergy resource and by calculating the exergy yield. Some final important considerations must be pointed out:

- Only domestic demand is analyzed, without considering energy resource exports.
- Only the energy consumption or *end use* of the energy resources is considered, whereas the production of electricity by using the various resources involved in the Colombian electricity mix is out of the scope of this study.
- *Own consumption* stands for the exergy necessary for a resource to be produced
- The losses in the own consumption are not analyzed.

As for the difference between the conventional approach and the propose methodology, it is worthy to notice that, the conventional OLADE methodology is chiefly based on the identification of four main components, namely the energy resources, the energy conversion systems, end-use systems as well as other processes non-classifiable into the main economic activities. By using the overall energy balances, this methodology aims to determine the breakdown of the energy resources consumption, either from the point of view of the specific end-use applications as well as from the economic sectors that they belong to. In other words, the OLADE methodology starts by identifying the source of the energy in the form of the primary energy resource, which is subsequently transformed by a defined set of energy conversion systems into a secondary

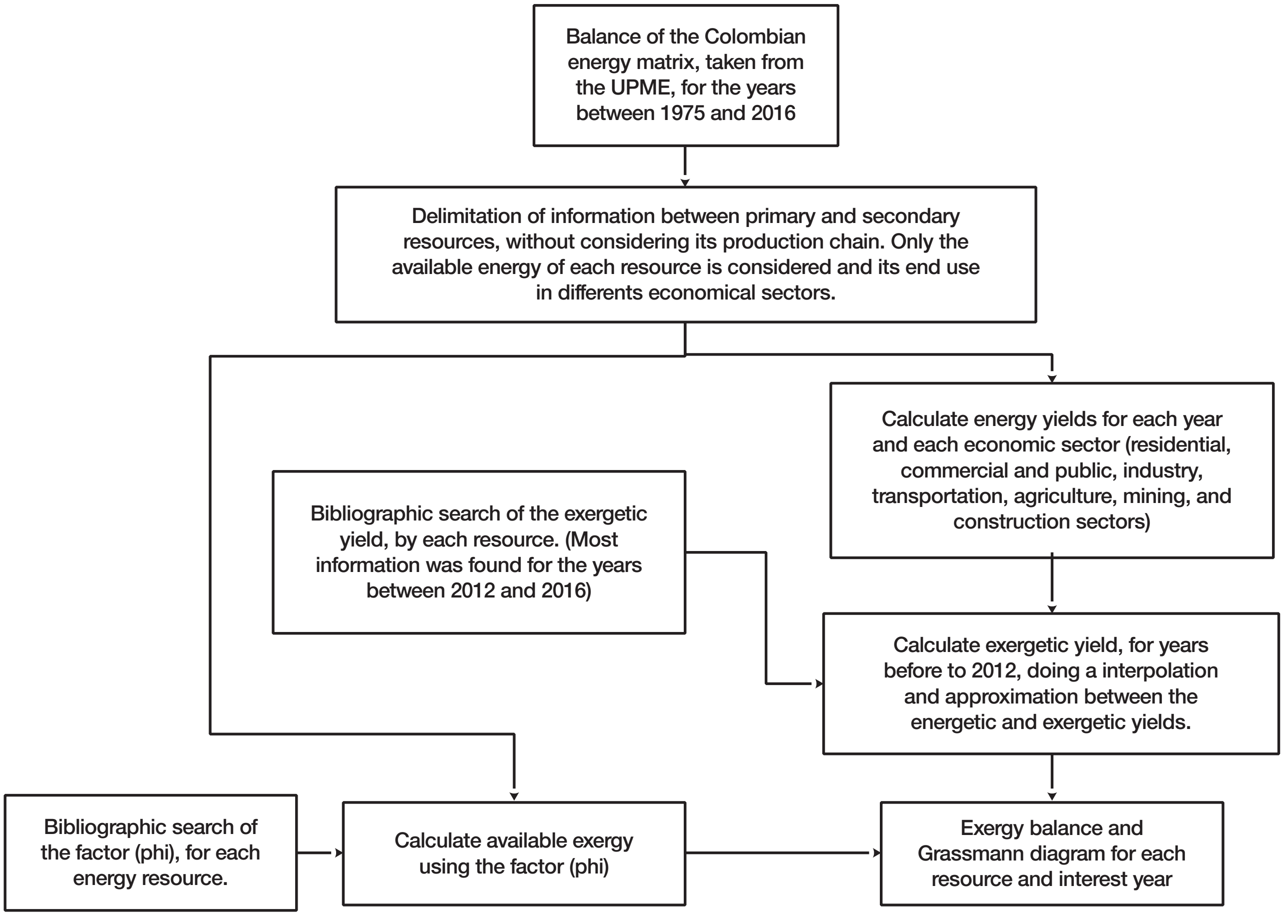

Figure 1: Scheme of the proposed methodology

source of energy, which is in turn consumed by an economic sector. Clearly, the intermediate energy conversion processes to produce secondary energy resources are achieved so that the value-added products can be more easily handled or more efficiently converted into other forms of energy. Finally, the OLADEs methodology aims to analyze the direct consumption or end-use of the primary and secondary energy resources.

For instance, petroleum is often considered a primary energy resource extracted at its natural conditions from the well. Thus, after extraction, the petroleum is partly exported out of the Colombian energy mix whereas the balance is transformed or consumed internally. The fraction of petroleum internally consumed could have been found in the early industrial sector, specifically in kilns and furnaces in the ceramics and cement industry. However, it is important to notice that, due to the more stringent environmental regulations, the direct utilization of petroleum as fuel has undergone important changes in the last years. This situation necessarily entailed the integration of improved energy technologies that better comply with the new environmental policies. On the other hand, the fraction of petroleum that is transformed into secondary energy resources, such as gasoline and kerosene, is supplied to the transportation sector, where the end-use stage (namely, the transportation service) is finally accomplished. Accordingly, each process stage has its respective energy efficiency, statistically calculated by OLADEs researchers by means of energy audits, aiming to identifying opportunities to reduce energy expense and carbon footprint, as well as to estimate the energy losses associated to each step of the process.

Since the exergy analysis is relatively recent and thus less widespread than the conventional energy-based analysis, there is a lack of reliable data of performance indicators, such as exergy efficiency of the different economic sectors. Thus, a detailed revision of the literature on the energy efficiency and consumption figures of those sectors (or similar suitable data) is performed, along with the adaptation of the energy performance of selected energy conversion processes to an exergy basis. This adaptation is possible thanks to the knowledge of the consumption of the energy resources consumed by sector and the thermodynamic properties of the substances and energy flow streams. Meanwhile, as long as the required data become progressively scarcer and often inconsistent for older years, it has been assumed that the exergy efficiency of the more recent scenarios can be extrapolated back to the older years analyzed. In other words, the exergy performance of the economic sectors evolves at rates that, at least, reflect the same trend observed in the energy performance of the various energy sectors throughout the time frame considered. Consequently, the exergy data is consistent with the energy figures reported and originally used in the OLADE methodology (energy-based only). Finally, it is also important to notice that most of the exergy figures reported in the literature are normally expressed in terms of the equipment component, unit operations or plantwide levels, but rarely in terms of the more comprehensive national energy sectors. Thus, in order to estimate the exergy efficiency of a given sector, the performance of representative energy technologies that dominate the operation of the respective economy sector have been considered.

2.1. Calculation of the input exergy flows of the energy resources

The calculation of input exergy flows is based on the data reported by the UPME for the Colombian energy mix. The exergy calculation of each energy input are determined by the ratio of the standard chemical exergy to the lower heating value (LHV), namely ϕ, which is a factor that proportionally relates the exergy and energy of an industrial fuel [11]:

$$B = \phi \, LHV \, m_r \quad (1)$$

where B is the exergy flow [in TJ], LHV is the lower heating value [MJ/kg], and m_r is the mass flow of the substance considered as material or fuel input resource. As for the lower heating value, the values reported in the Colombian energy balance report have been assumed [23]. It is important to notice that the reference dead state used in the calculation of the chemical exergy of the resources consumed assumed as that proposed in Szargut et al. [4]. Thus, the values of the ϕ ratio can be calculated by using the Eqs.(2–6) and the obtained results are comparable to those reported in the literature [24].

The ϕ for gaseous fuels with mass hydrogen to carbon ratio (H/C) and a number of carbons (N_c) in the chemical composition:

$$\phi_{dry} = 1.0334 + 0.0183(H/C) - 0.0694(1/N_c) \quad (2)$$

For liquid fuels with hydrogen to carbon (H/C) and oxygen to carbon (O/C) ratios (mass basis):

$$\phi_{dry} = 1.0374 + 0.0159(H/C) - 0.0567(O/C) \quad (3)$$

For solid fuels composed by dry organic substances with hydrogen to carbon (H/C), oxygen to carbon (O/C) and nitrogen to carbon (N/C) ratios (mass basis) in their chemical composition and subject to O/C < 0.5 (No applicable for wood):

$$\phi_{dry} = 1.0437 + 0.0140(H/C) - 0.0968(O/C) + 0.0467(N/C) \quad (4)$$

For solid fuels composed by dry organic substances with hydrogen to carbon (H/C), oxygen to carbon (O/C) and nitrogen to carbon (N/C) ratios (mass basis) in their chemical composition and subject to 0.5 < O/C < 2 (Applicable for wood):

$$\phi_{dry} = \frac{1.044 + 0.0160(H/C) - 0.3493(O/C)[1 + 0.0531(H/C)] + 0.0493(N/C)}{1 - 0.4124(O/C)} \quad (5)$$

For other liquids such as petroleum derivatives, containing sulfur:

$$\phi_{dry} = 1.0401 + 0.1728(H/C) - 0.0432(O/C) + 0.2169(S/C)[1 - 2.0628(H/C)] \quad (6)$$

One exemption is clearly the electric power coefficient ($\phi - 1$), as it can be considered as a fully organized type of energy interaction. Actually, in the ideal case, the electric power could be fully converted into other forms of energy, regardless of the restrictions imposed by the Second Law of the Thermodynamics (*Clausius Postulate*) to the conversion of the chemical exergy of the complex substances and industrial fuels shown in Table 1. The electricity consumed is considered as readily available to be used in the economic

Table 1. Resources and factor used for the exergy calculation of the Colombian energy mix input exergy flows

Identifier	Resource	ϕ [reference]	LHV (MJ/kg) [23]	Specific Chemical Exergy (MJ/kg)
BS	Bagasse	1.07 [25]	19.2	20.5
CO	Coal	1.03 [24]	32.7	33.7
NG	Natural gas	1.16 [24]	39.9	46.3
FW	Firewood	1.07 [24] [25]	19.0	20.3
OL	Oil	1 [24]	40.9	40.9
FC	Firewood coal	1.04 [24]	31.4	32.7
DO	Diesel oil	0.99 [26]	43.0	42.6
EE	Electric power	1 [27] [26]	–	–
FO	Fuel oil	0.99 [26]	43.8	43.3
BG	Blast furnace gas	1.06 [26][24]	46.4	49.1
LG	Liquefied petroleum gas	1.06 [26] [24]	45.8	48.5
PT	Petrol	0.99 [26]	43.9	43.5
RG	Refinery gas	1.06 [24]	39.9	42.3
KJ	Kerosene and jet fuel	0.99 [26]	43.9	43.5
EF	Ethanol fuel	1.07 [25]	26.8	28.7
BD	Biodiesel	1.2 [25]	37.2	44.6

sectors of the Colombian energy mix. Thus, the overall losses associated to its production already accounts for the inefficiencies of its generation and distribution to the different consumers, namely the various economic sectors.

It is also important to bear in mind that, as long as exergy losses and unavoidable irreversibilities associated to the energy degradation are considered together as an irremediable loss, the opportunity of the economic systems to produce a useful effect is lost. In other words, losses and irreversibility are indistinctly considered, regardless loss is owed to the internal irreversibilities of the industrial systems or due to the release of wastes that otherwise could be further transformed into value-added products through more advanced energy conversion process that are not yet available in our specific energy mix.

2.2. Selected exergy yields for each economic sector

Transportation sector encompasses the whole energy consumption in the transportation service, public or private; national or international; passenger or freight transport; in land, sea or air. Industrial sector involves the energy demands of all the industrial activities and end-uses, except for the transportation of the merchandises, which is already included in the transportation sector. Actually, the fastest development of the industrial sector of the growing Colombian economy led to different increase rates of the efficiency of these energy conversion processes, if compared to the residential, transport and farming sectors. Residential sector includes all the energy consumptions required to satisfy the requirements of the urban and rural households, such as cooking, illumination, refrigeration and so forth. Agriculture and mining sectors encompass the energy consumption in the activities associated to the obtainment of the feedstock, livestock farming, and ore extraction. Own consumption stands for the energy consumption along the production and transportation of the primary and secondary energy resources. In other words, it is the energy required to bring about the energy resource itself. Sectors that are not classified into the previously mentioned ones, such as construction, infrastructure, among others, are classified into the category of other consumption. Table 2 shows the energy yields calculated for 2012, in which n/a refers to the sectors in which the resources are not consumed. In average, the energy consumption in the residential and industrial sectors presents an efficiency of 60 and 76% [28][29], respectively, whereas the commercial sector is assumed to behave similarly to the residential one, setting its efficiency about 76% [30] [29]. Transportation sector the end use efficiency of diesel, natural gas, gasoline and kerosene oscillates between 15 and 22% [31]. Those figures show the important weight of the transportation sector on the overall efficiency of the countries, if compared to the reported values of USA, Finland, Canada, Brazil, Saudi Arabia, Turkey and Norway, ranging

Table 2. Energy yield as a function of each resource and economic sector, calculated by means of the BECO balance for year 2012 (in %)

Resource	Residential	Commercial	Industrial	Transportation	Farming	Construction	Unidentified	Overall
BS	n/a	n/a	65,5	n/a	n/a	n/a	54,1	63,0
CO	n/a	n/a	67,1	n/a	n/a	n/a	n/a	67,1
NG	70,0	70,0	72,0	30,0	n/a	n/a	65,8	64,7
FW	10,0	n/a	30,1	n/a	n/a	n/a	n/a	10,1
OL	n/a	n/a	19,7	n/a	n/a	n/a	n/a	19,7
FC	n/a	n/a	13,3	n/a	n/a	n/a	n/a	13,3
DO	n/a	n/a	61,4	18,2	n/a	n/a	20,9	19,5
EE	80,0	80,0	82,0	81,8	55,0	54,9	75,1	78,4
FO	n/a	n/a	73,4	25,9	n/a	n/a	72,0	72,5
BG	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
LG	64,6	60,2	66,3	n/a	n/a	n/a	55,6	63,1
PT	n/a	n/a	14,9	14,5	n/a	n/a	14,9	14,6
RG	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
KJ	n/a	n/a	14,7	18,2	n/a	n/a	14,7	18,0
EF	n/a	n/a	n/a	18,0	n/a	n/a	n/a	18,0
BD	n/a	0,0	0,0	18,2	0,0	0,0	n/a	14,7
Overall	52,8	76,1	70,3	17,5	46,4	48,6	33,1	42,1

between 35 and 50% [28]. The exergy yields in each economic sector for each year allow calculating the exergy losses and estimate end use performance. For other years, the energy yields are preliminary assumed to increase linearly along the time. In Table 2, unidentified sector accounts for all other energy conversion systems that are not related to the main economic activities (residential, commercial, transport, etc), as reported in the BECO balance reported by the UPME

2.2.1. Literature review on exergetic yields

The exergy yields in the residential sector are of 5.8% [32] for CO, 5.50% [27] for NG, 5.80% [27] for FW, 5.80% [32] for FC, 12% [22,23] for EE, and 13% [26] for LG. These exergy yields have been determined by assuming that the use of those fuel resources was primarily intended for cooking, lighting, and handling electronic devices. Meanwhile, for the commercial and public sectors, an exergy yield of 12% [26] is adopted for EE resource, mainly used for illumination and handling of electronic devices in these sectors.

The industrial sector reportedly presents an exergy yield of 40% [21-23,25] for the use of BS as an energy agent in sugar cane mills. Additionally, an exergy yield of 26% [22,23] is considered for the utilization of CO in the cement and metallurgical sectors, whereas an exergy yield of 26% [23,26] is found for NG due to its fundamental usage in the chemical and cement production sectors. In the case of EE resource, an exergy yield of 7% is reported [26] for its use in lighting, heating, as well as for driving electric motors and electronic devices. Finally, exergy yields of about 25% [26] and 13% [26] are adopted for the utilization of FO and BG resources due to their use mainly in machinery and in the iron and nonferrous steel industries, respectively.

The exergy yields in the transportation sector are of 12% [26] for PT, 39% [22,27] for DO, 25% [22,23] for NG, 54% [36] for KJ, 35% [37] for EF, and 35% [21,27] for BD. These yields have been calculated based on the use of the resources for the operation of internal combustion engines in land, sea, and aviation transportation. Lastly, for the agriculture and mining sectors, a yield of 8% is found [21,22], which was based on the use of BS in the cane sugar mills.

Finally, it is worthy to notice that, due to the lack of reliable data on exergetic efficiency for the years 1975, 1993 and 2012, the data obtained for 2016 have been used to perform a regression that allows the study of the previous years to be carried out in an approximate way.

Given the energy yields for the different resources consumption through all the various economic sectors and the conversion factor ϕ defined in Eq.(1), the overall

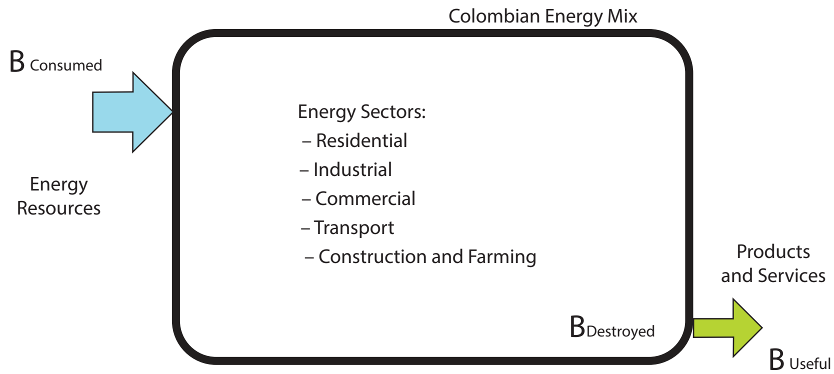

Figure 2: Control volume used for the calculation of the exergy efficiency of the energy consumption in the Colombian energy mix.

exergy efficiency of the nationwide economic activities can be calculated by using the Eq.(7) and the control volume represented in the Fig. 2:

$$\eta = 1 - \frac{B_{destroyed}}{B_{consumed}} = \frac{B_{useful}}{\sum(\phi\ LHV\ m_r)_{sector}} \quad (7)$$

The system boundary encloses the existent economic activities responsible for the energy resources consumption in the Colombian energy mix. Therein, the inputs are the different resources consumed and the outputs are the different useful exergy flows, eventually used to drive the economic activities in the different economic sectors. Therefore, the Grassmann diagrams already correspond to the schematic representations of the exergy balances of the system. Accordingly, the useful exergy stands for the exergy that is eventually used to drive the economic activities in the different economic sectors. They are defined in terms of the energy yields converted into exergy yields by using the thermochemical properties and composition of the energy resources considered for each sector.

3. Results and discussion

In this section, the exergy analyses based on the Grassmann diagrams are performed. It is important to bear in mind that, in this diagram, the arrows are representations of the input, intermediate or output exergy flows throughout the entire domestic energy mix, such that the width of the arrow is proportional to the magnitude of the flow. Furthermore, differently from the analogous Sankey diagram, based on the First Law of the Thermodynamics (*Energy Flow Conservation*), Grassmann diagram incorporates the representation of the amount of irreversibility produced along the energy conversion process. This is readily perceptible from the reduction of the width of the energy flows while going through certain energy industrial activity. Thus, in the following sections, an analysis based on the exergy losses associated to the energy resources is initially performed. Next, a second study is carried out in order to quantify the amount of exergy destroyed among the various economic sectors. Finally, the gradual impact of the variation of the resources consumption profile on the energy efficiency, the current dominant energy resources and its effect on the economic and societal behaviors is briefly discussed.

3.1. Grassmann diagrams: analysis from the perspective of the energy resource

In Figures 3-6, Grassmann diagrams show the exergy losses associated with the use of the different fuels. In those diagrams, “unidentified” sector accounts for all other energy conversion systems that are not related to the main economic activities (residential, commercial, transport, etc.), as reported in the BECO balance reported by the UPME.

As it can be seen from Figure 3, back to 1975, firewood played the most important role as exergy resource (26%) in the domestic energy mix in Colombia. This fact is explained by the higher percentage of rural population (41.5%) [38] and the higher costs of electricity [39]. Other important resources in the Colombian economy in the year 1975 were petrol, fuel oil, and coal, with contributions of about 20%, 9%, and 8%, respectively. Other important observation for the year 1975 is that the productive sectors with the lion’s share in the Colombian economy were those sectors that most efficiently used the consumed resources. Additionally, it can be observed

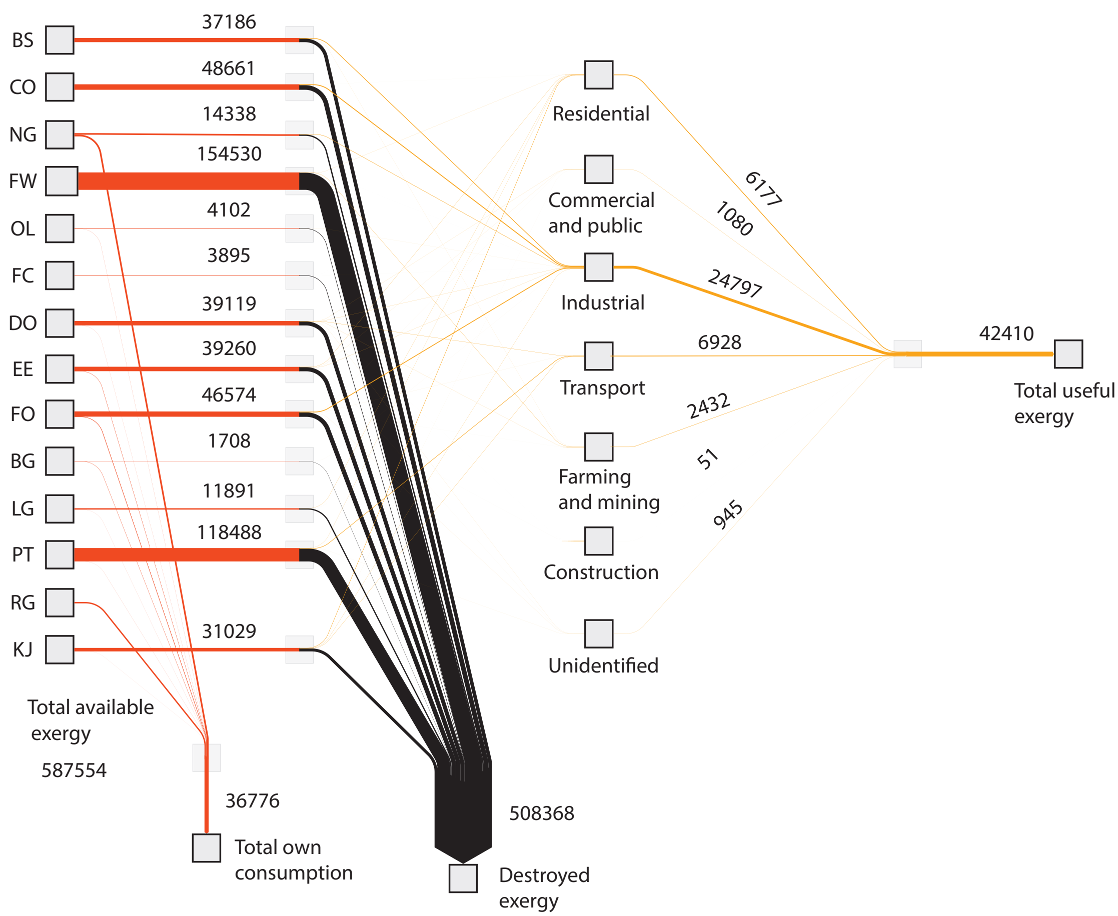

Figure 3: Use of exergy resources in the Colombian economic system for the year 1975, a view from losses by resource. Grassmann diagram in TJ

that firewood and petrol also led to the main sources of exergy destruction due to the inefficient use of these resources.

Figure 4 shows the Grassmann diagram for the year 1993, in which petrol, firewood, electric energy, diesel, and coal were the predominant fuels in Colombia, with a respective participation in the domestic demand of about 25%, 15%, 12%, 11%, and 10% respectively. As it can be seen from this figure, there is a substitution of firewood by petrol, as well as an increase in the demand for other resources, such as diesel and electric power. This circumstance could be partially explained by the implementation of new policies related to the thermoelectric generation [40] and the increase in the vehicle fleet in Colombia [41], obeying the increasing trend of the population growth.

Back to the year 2012 (see Figure 5), natural gas, diesel, electricity, and motor gasoline were the resources with the largest participation in the Colombian economy with 16%, 21%, 14%, and 14%, respectively. It is also observed the introduction of new energy resources, such as alcohol fuel (EF) and biodiesel (BD) in the economy, but still representing a small share of 0.6% and 1.7%, respectively. It is also observed from Figure 5 that two resources are already missing from the exergy mix, namely the blast furnace gas (BG) and the refinery gas (RG). It can be also evidenced an sharply increased dependence on fossil fuels over time, largely due to the evolving domestic energy demand as Colombia has gradually become a major fossil fuel producer, exporter and consumer. Actually, since the major basin discoveries and the industrialization of the country, petroleum derivatives, natural gas as well as coal represent about 50% of the exported energy commodi-

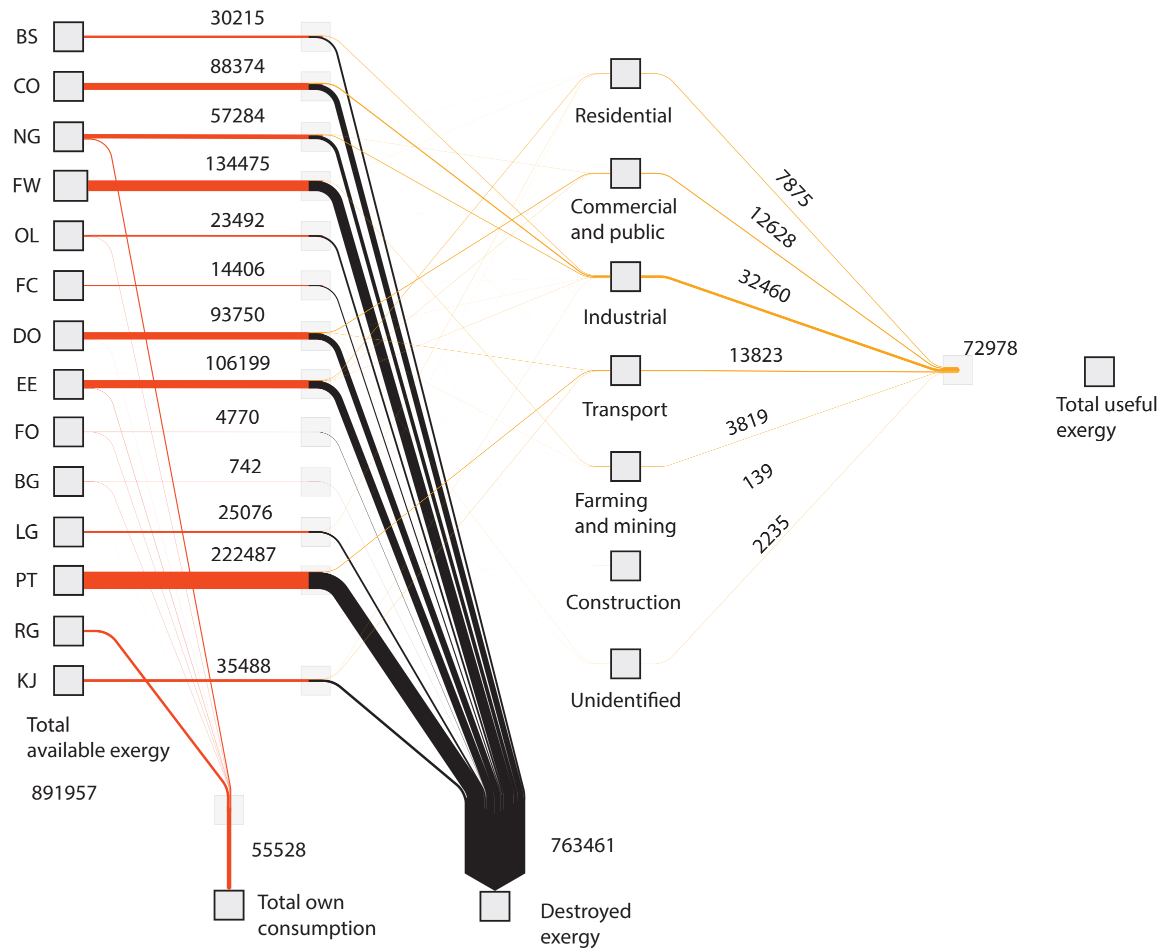

Figure 4: Use of exergy resources in the Colombian economic system for the year 1993, a view from losses by resource. Grassmann diagram in TJ.

ties, with the Colombian Petroleum company, ECOPETROL, corresponding to the largest Colombian enterprise in terms of economic revenues and stock exchange trading, and the second largest petroleum company in Latin America [42].

It must be said that the values of exergy for OL and FC are so small that their lines in Figure 5 cannot be observed. In addition, the UPME did not report the exergy values for BG and RG in the year 2016. On the other hand, the principal energy resources are fossil fuels, but other fuels like ethanol and biodiesel are gradually introduced with a share of 1% and 2% respectively in the energy mix, due to the implementation of the governmental programs that compel the utilization of blended fuels in the automotive sector. Furthermore, Figure 6 shows the important share of DO, PT, and NG as the main energy resources with a participation of 19%, 18%, and 17% in the energy mix, respectively, reinforcing the radical change of the resource consumption over the time. It can be explained by the fact that Colombia has become not only a fossil fuel producer and but also an important consumer, aggravated by the incipient interest in renewable energy policies except for the hydroelectric power contribution and the electricity generation in sugar cane biorefineries. For instance low-ash, low-sulphur bituminous coal Colombian mine “El Cerrejon” is one of the largest of its type, the largest in Latin America and the tenth biggest in the world [43].

According to the aforementioned analysis of the evolution of Colombian energy mix, a transformation of the country from a rural into an urban-centered economy can be clearly evidenced. Actually, in the last decades, Colombia rapidly increased the use of a more diversified set of energy resources as a response to its rapid

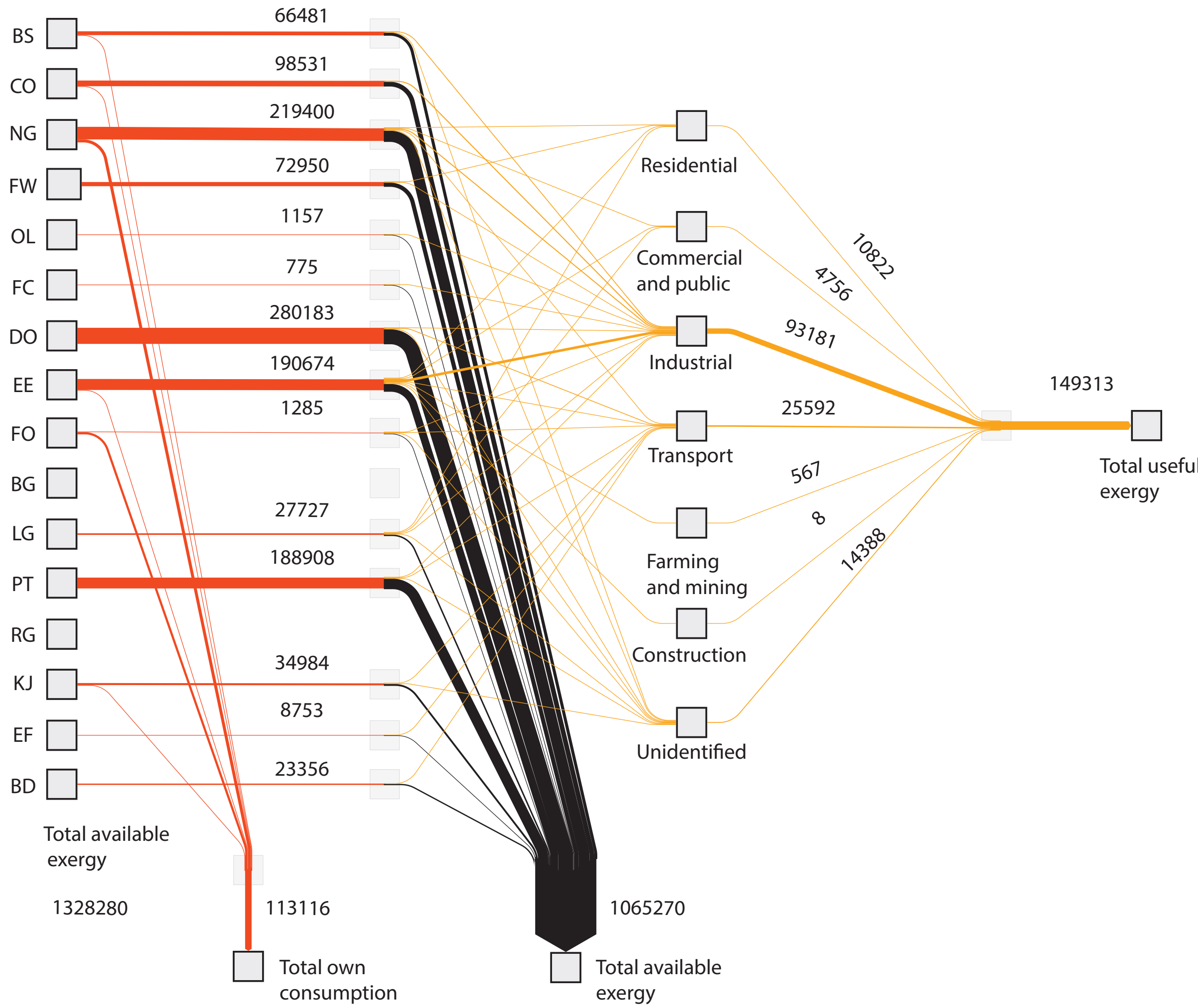

Figure 5: Use of exergy resources in the Colombian economic system for the year 2012, a view from losses by resource. Grassmann diagram in TJ

economic development averaging 2-4% in the last decade, the increased population growth and more dynamic economic sectors. Unfortunately, this economic growth has not been suitably planned from the beginning, always being subject to many other economic, geopolitical and social problems that finally led to more rigorous, but still not sufficient, energy and environmental regulations for the sustainable exploitation of its natural resources.

3.2. Grassmann diagrams: analysis from the perspective of the economic sectors

Figure 7 shows the Grassmann diagram for the year 1975. As it can be seen, firewood, petrol, and coal were the resources with the largest participation in the Colombian economy mix. It can also be observed that the residential sector used to play a more important role with about 33% of the energy consumption share, followed by transportation sector (25%) and the industrial sector (24%).

Likewise, Figure 7 shows that in the residential sector, the use of firewood was predominant, whereas in the transportation sector, petrol consumption represented the largest proportion. The industrial sector, on the other hand, was controlled by coal and fuel oil. In addition, in 1975 the residential sector presented the largest exergy losses, when compared to other economic sectors, due to the inefficiencies in the use of firewood in households and other rural activities.

The Grassmann diagram for 1993 is shown in Figure 8. In this figure, the large participation of the transportation sector (33%), industry (24.5%), and residence (24.4%)

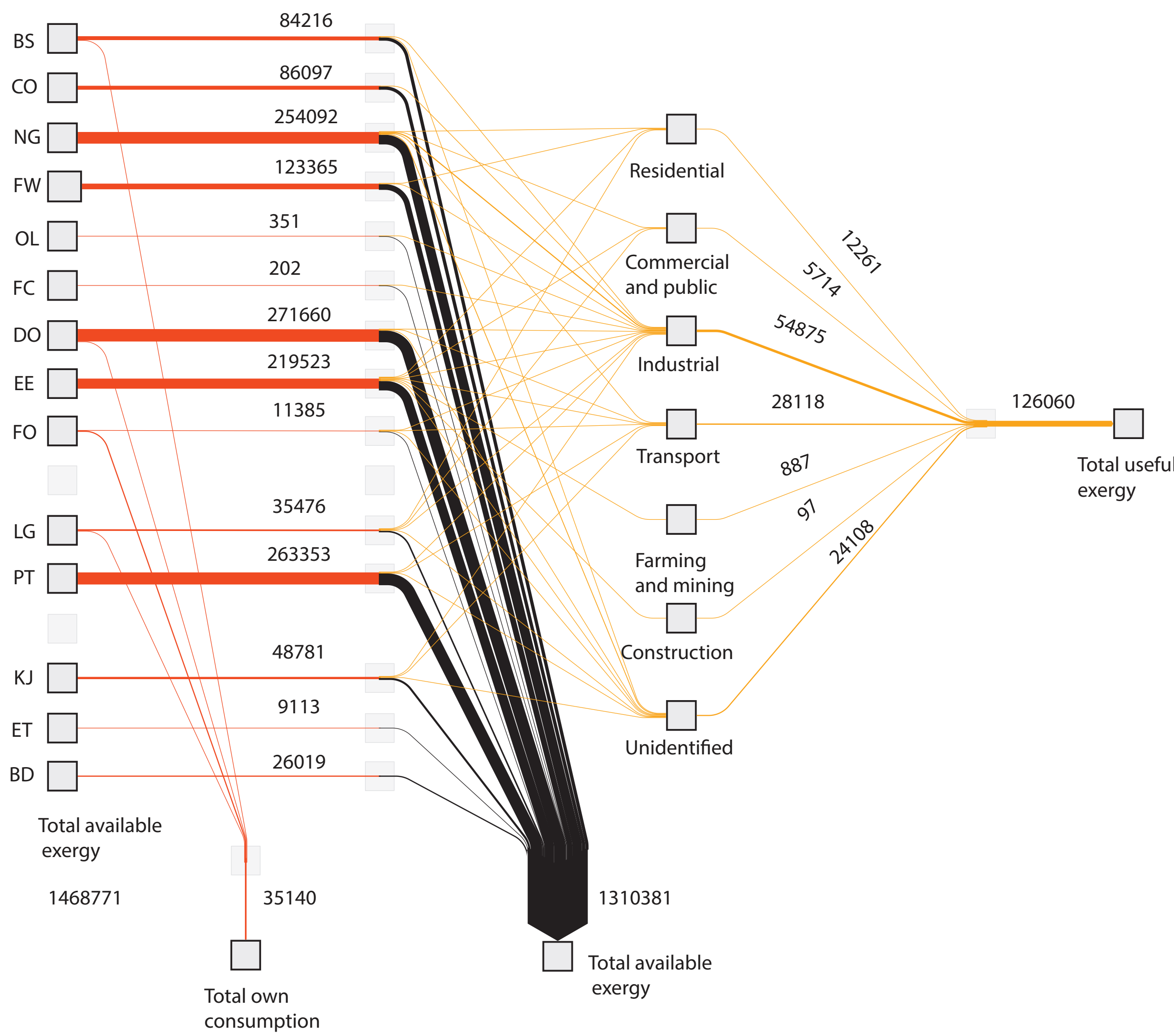

Figure 6. Use of exergy resources in the Colombian economic system for the year 2016, a view from losses by resource. Grassmann diagram in TJ

sectors in the Colombian economy can be observed. It can be also seen an increase in the participation of the transportation and industry sectors, and a decrease in the residential sector share. It is also observed the progressive replacement of some resources, with an increase in the consumption of electric energy and, consequently, a decrease in the firewood demand in the residential sector.

On the other hand, Figure 9 illustrates the Grassmann diagram for the year 2012, in which the transportation (33%), industrial (23%), and residential sectors (15%) become the most significant sectors in the Colombian economy in terms of energy demand. It can be also observed a partial replacement of firewood by natural gas and electricity in the residential productive sector, as well as the partial substitution of natural gas in the industrial sector. Similarly, in the transportation sector, diesel finally replaced petrol as the main fuel for the heavy duty and urban transportation fleet. This is simultaneously reflected in an increased performance of the end use of vehicle fuels, since the diesel combustion engines stand for higher conversion efficiencies, than that of petrol-based applications. Notwithstanding, although less considered, a secondary, harmful environmental impact may be triggered by increasing the circulation of diesel-fueled heavy-duty trucks and a more polluting even though efficient bus fleet, compared to the natural gas-powered or electric battery-driven alternatives. In fact, the transportation sector increases its participation in the Colombian economy up to 37%,

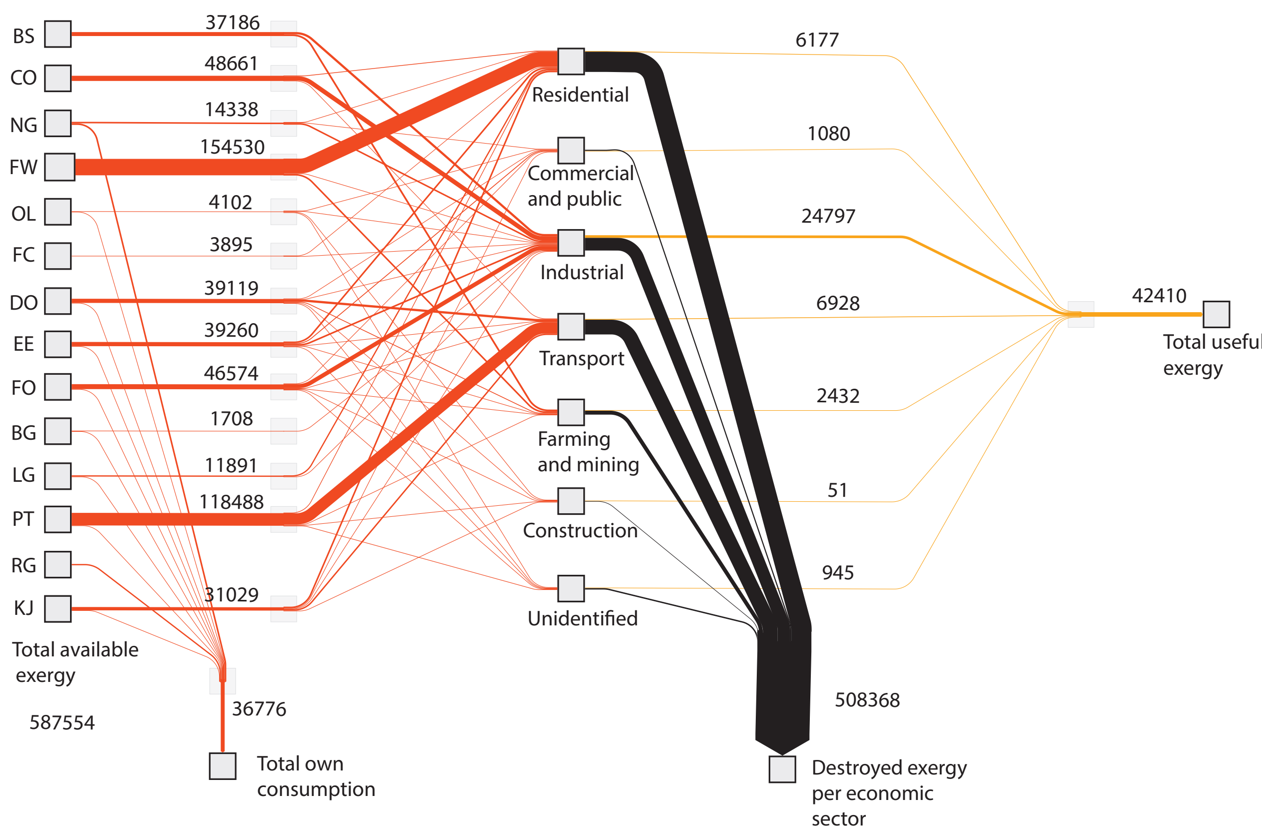

Figure 7: Use of exergy resources in the Colombian economic system for the year 1975, a view from losses by economic sector. Grassmann diagram in TJ

which evidences the dominant importance of this sector in the country, followed by the industrial and residential sectors, with a participation of 24% and 19%, respectively. It is important to notice that, although farming and mining are also considered among the most important sectors in terms of exergy intensity, they present a reduced participation in the energy and economic system, representing with only 1% in the economic and exergy mixes.

Finally, by comparing Figures 3-9 and Figure 10, the latter one corresponding to the Grassmann diagram for the year 2016, a gradual substitution of the resources in the economic sectors can be evidenced. In fact, in the year 1975, the residential sector was responsible for the predominant contribution to the domestic exergy consumption, since the Colombian economy was going through the very early deployment of its industrial sector back then. However, at the same time that the Colombian economy assumed its role as the third largest Latin American market, the residential sector was replaced by the industrial sector as the most important economy sector, which, in turn, was superseded by the transportation sector in the recent decade. Furthermore, since 1975 until now, firewood and petrol were progressively exchanged by the use of other resources like NG, DO, EE, and PT.

3.3. Overall exergy analysis of the performance of the Colombian economic sectors

The development of the representative Colombian economic sectors (namely, residential, industrial, transportation and farming/mining sectors) over the time is compared in Figure 11.

According to Figure 12, although the Colombian population has largely increased since 1975, the residential sector shows a lower rate of growth of exergy

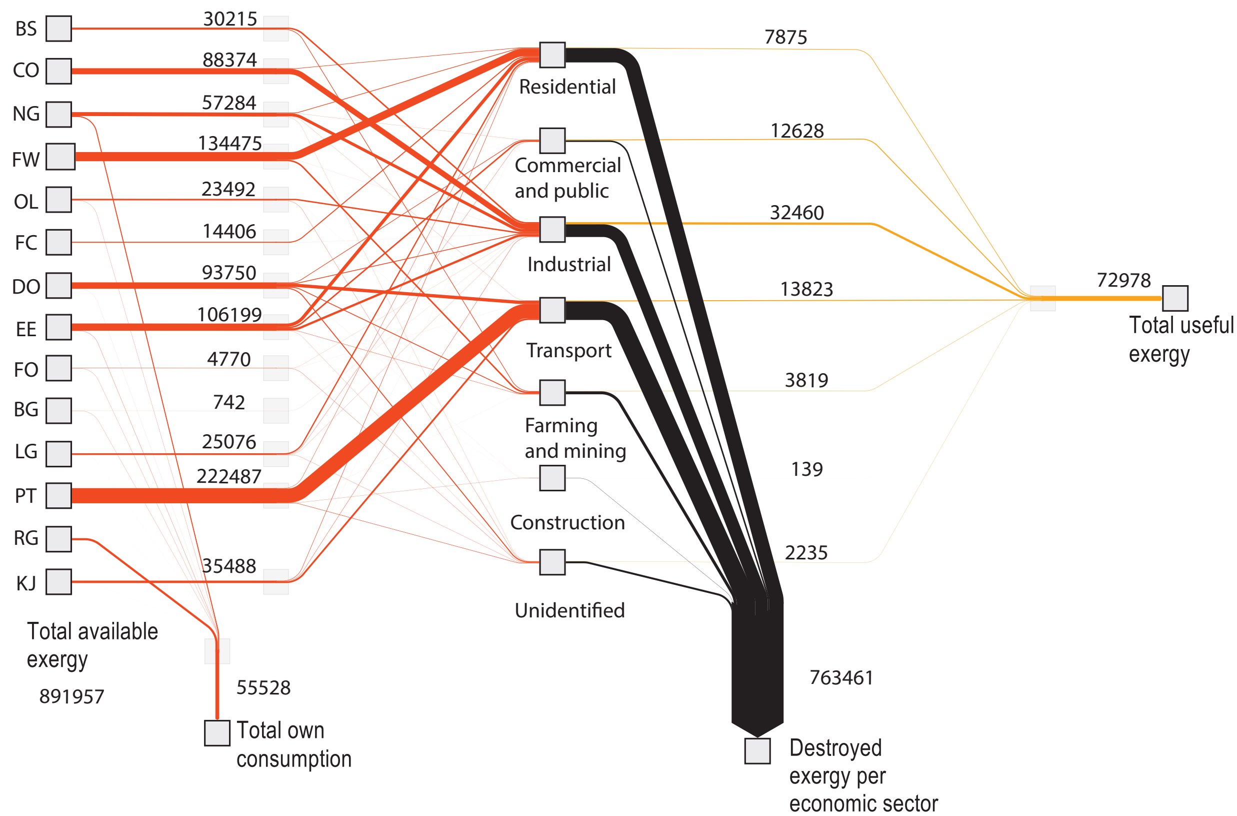

Figure 8: Use of exergy resources in the Colombian economic system for the year 1993, a view from losses by economic sector. Grassmann diagram in TJ.

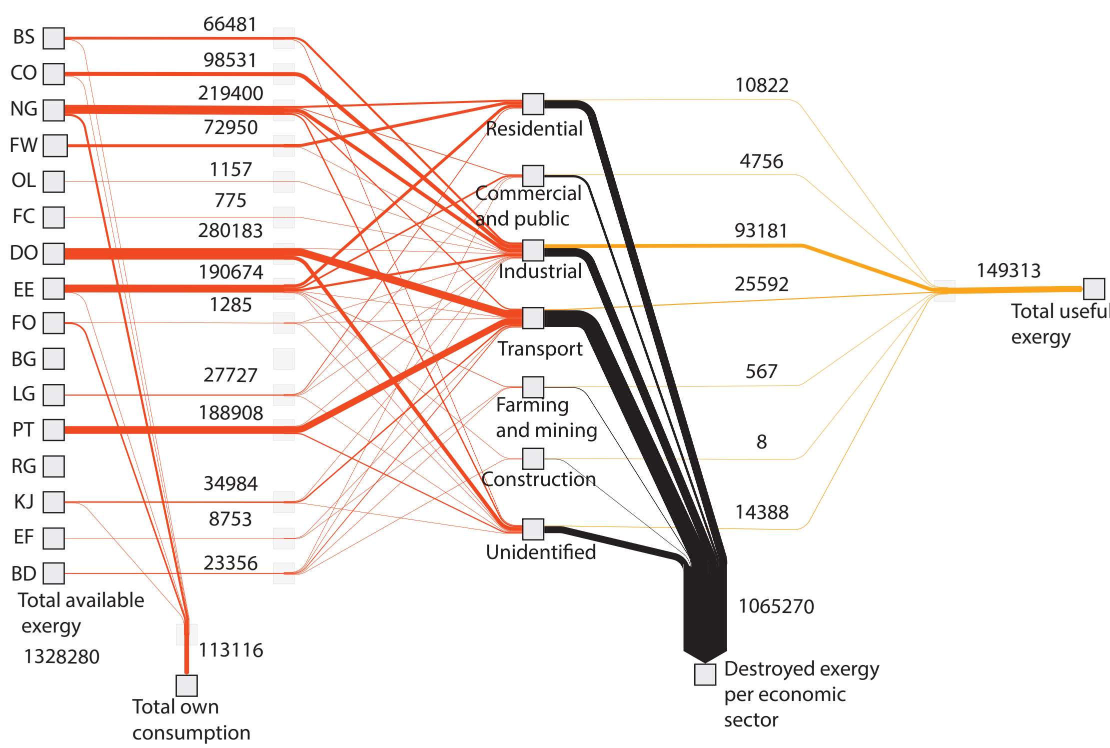

Figure 9: Use of exergy resources in the Colombian economic system for the year 2012, a view from losses by economic sector. Grassmann diagram in TJ

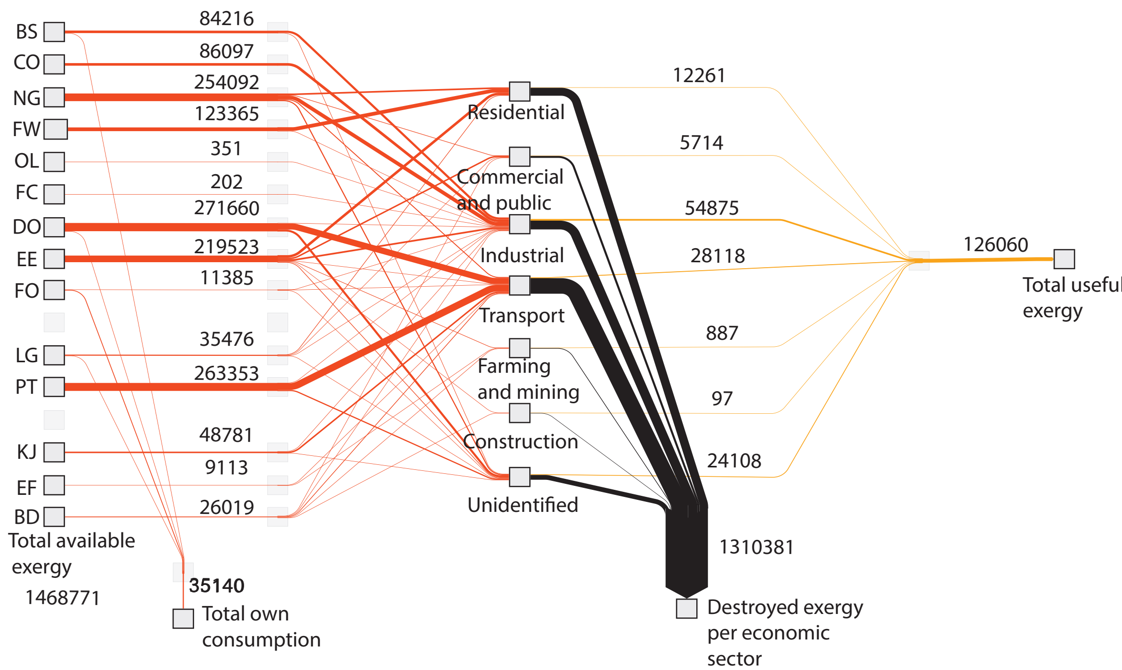

Figure 10. Use of exergy resources in the Colombian economic system for the year 2016, a view from losses by economic sector. Grassmann diagram in TJ

consumption compared to the respective rates of industrial and transportation sectors. On the other hand, the farming and mining sectors remain almost invariable in terms of low exergy consumption along the analyzed years. Another important point is that the industrial sector seemingly uses the energy resources consumed more efficiently than the remaining sectors, namely the residential, transportation, and farming sectors. Despite this fact, the overall energy efficiency increase in the country is rather low, as it can be observed from the evolution of the exergy efficiency in the Colombian exergy mix over the time shown in Figure 12. This evolution is expectedly associated to the technological development that Colombian sectors have gone through the last years, showing an improvement in the use of the thermodynamic potential of the energy resources, the most significant corresponding to the change between 1975 and 1993.

According to Figure 13, the absence of any coordinated technical, technological, political and societal revolution has hindered a significant reduction of the overall irreversibility of the overall economic system in the last four decades. In this way, more than 95% of the total exergy consumed in the Colombian energy mix has been irremediably destroyed, generating thus a thermodynamic and environmental impact that widens the development lag respect to other global economies. Certainly, the current shift to a modern, industrialized country and the substitution of less efficient cooking and district heating practices, such as firewood combustion, has led the rural areas to an increased level of exergy performance. Furthermore, in the late 90s, the massification of the access to natural gas for cooking instead of using electric heaters in showers, furnaces and stoves, led to a slight increase in the efficiency of those systems. It is also worthy to notice that, since most of the agriculture and residential residues do not have a comprehensive recuperation policy, ending up in landfills and even worse disposed into complex ecosystems, a huge thermodynamic potential coming from the upgrade of the industrial, residential and agriculture wastes is inevitably destroyed.

Additionally, it is interesting to analyse the evolution of the use of some important resources that reshaped the energy and economic figures of the Colombian energy mix. Figure 12 depicts the natural gas production, domestic demand, final consumption, useful exergy as well as the exergy losses over the time frame studied. It is important to notice that the useful exergy available remains almost steadily low over the time, regardless the

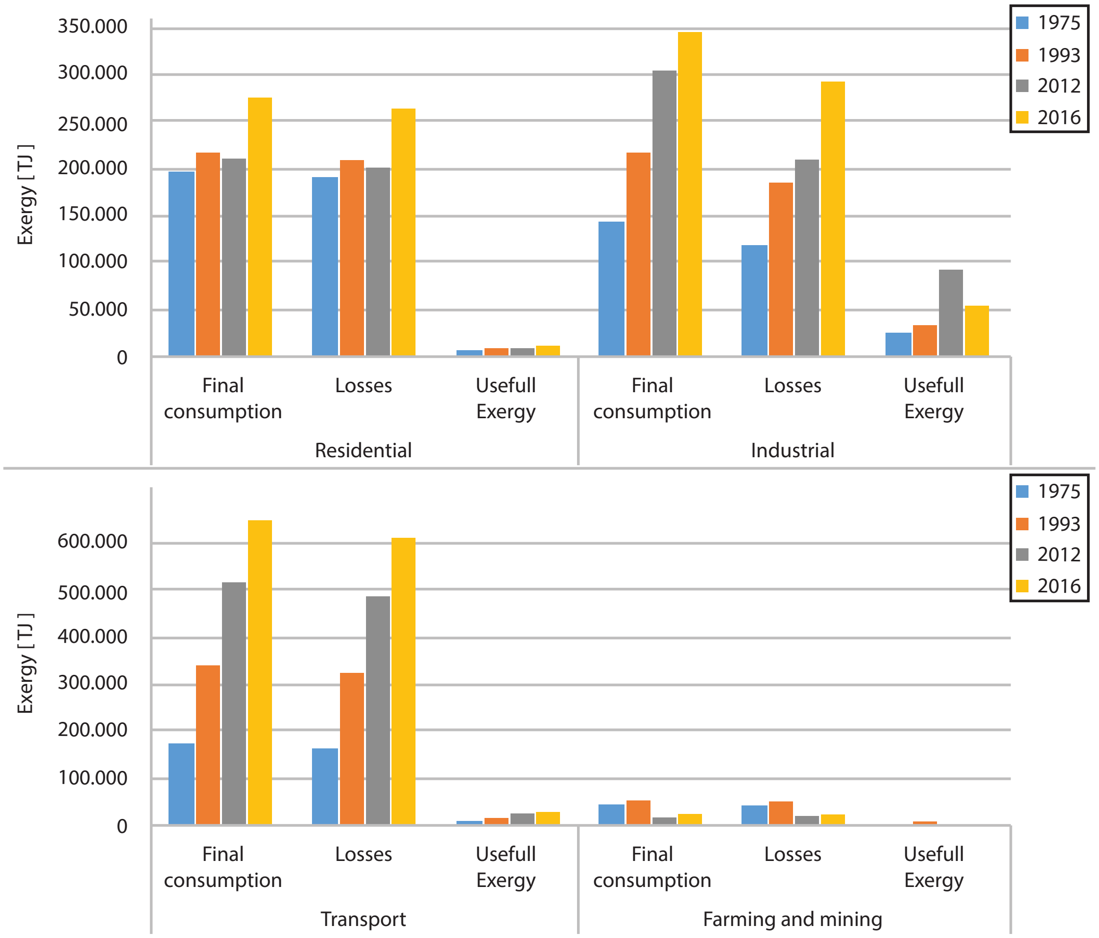

Figure 11. Use of energy resources in Colombia in the main economic sectors

domestic demand or the exergy losses, accompanied by a striking variation in the consumption rate of the domestic demand of this resource.

Analogously, Figure 14 shows the production, domestic demand, final consumption, useful exergy and exergy losses of the Colombian electricity over the time. Again, the significantly low available useful exergy over the time is independent from the domestic demand or the exergy losses. Meanwhile, a slight increase in the domestic demand is observed, which is in agreement with the constant population and industrial growth rates along the studied years.

Finally, Figure 15 shows the firewood production, domestic demand, final consumption, useful exergy and exergy losses in the same interval. As it can be seen, there has been a marked decrease in the firewood production brought about by the substitution of this resource by other resources, such as electricity. Although firewood is the resource that presents the largest

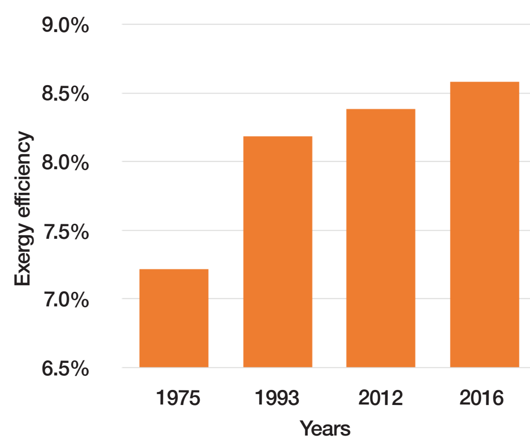

Figure 12. Evolution of the overall exergy efficiency of the Colombian energy mix over the time

inefficiencies in the end use, this fact does not necessarily implies that the other resources presented in Figures 13

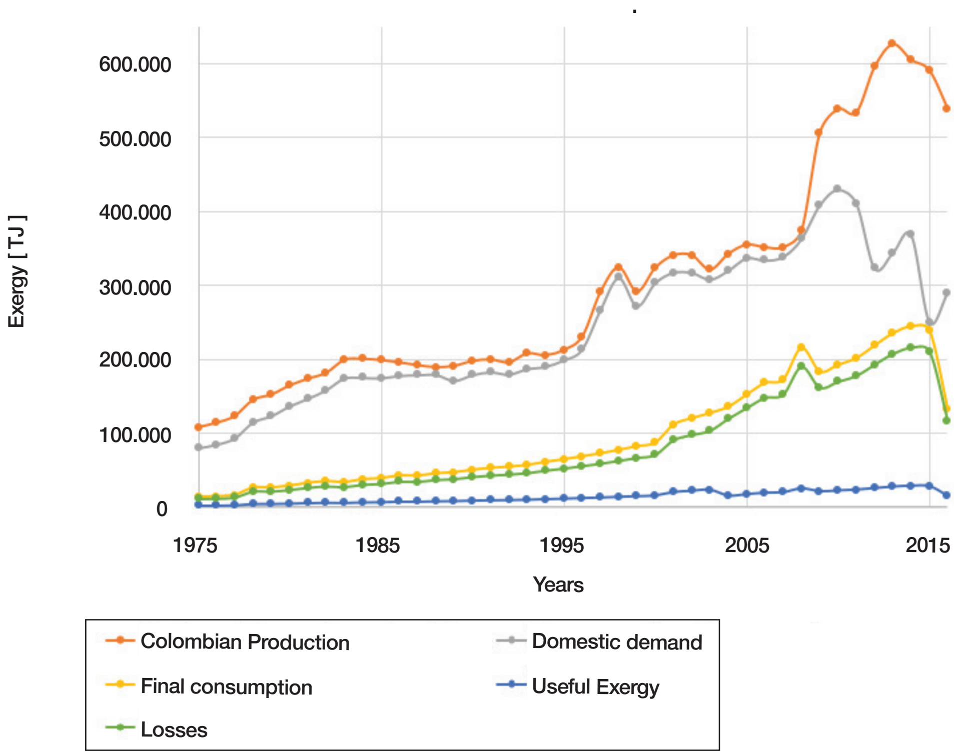

Figure 13. Evolution of the use of the natural gas exergy resource through 1975 – 2016

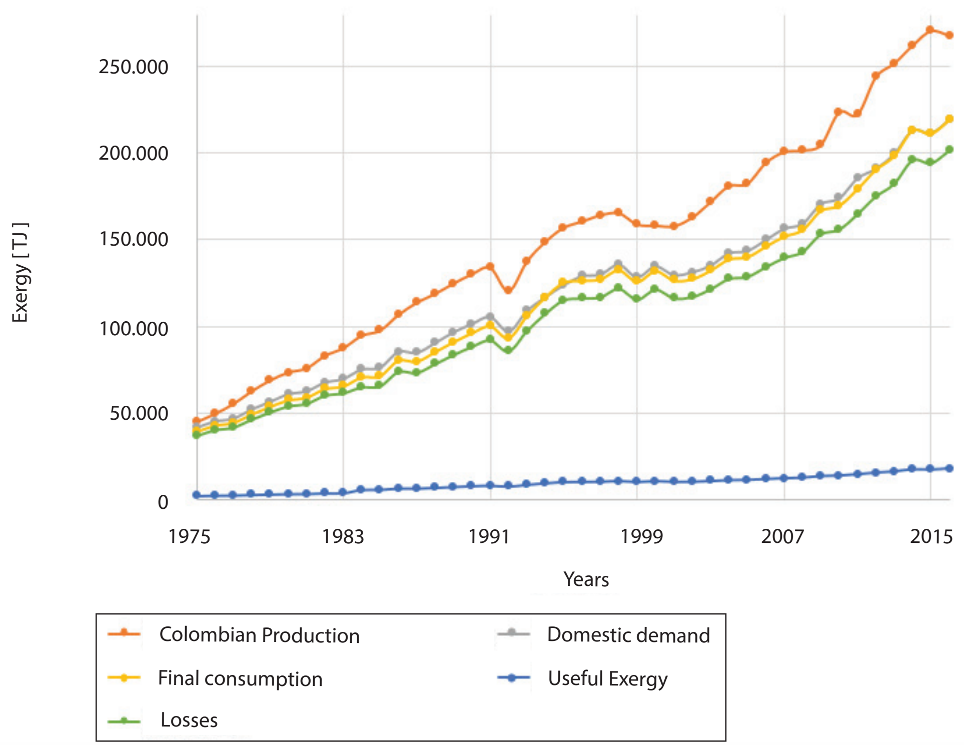

Figure 14. Evolution of the use of the electric power exergy resource through 1975- 2016

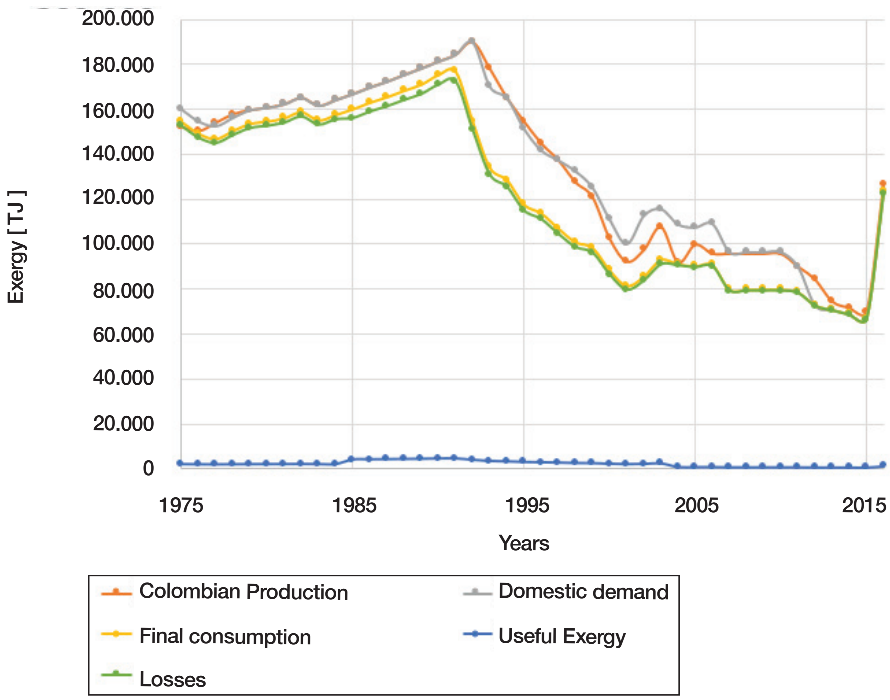

Figure 15. Evolution of the use of the firewood exergy resource through 1975 -2016

and 14 outperform the former in terms of the utilization of their total thermodynamic potential, given by their exergy efficiency.

As a final remark, it is important to notice that, as the second most biodiverse country in the world [44], and the most biodiverse by extension, after Brazil, the energy planning and economic development of Colombia is admittedly more difficult but also more relevant, and requires a more careful economic and thermodynamic analysis than other geographical regions. Accordingly, the impact of the energy conversion systems must not only take into account aspects related to economic criteria in order to issue the future energy policies, but also look for increased exergy efficiencies that simultaneously attempts reducing the environmental impact generated by the human activities.

4. Conclusions

In this work, a study of the evolution of the consumption of the energy resources in the Colombian energy mix is performed. The study is carried out by using the concept of exergy (combination of the First and Second law of the Thermodynamics) and takes into account the performance of four different time frames, namely 1975, 1993, 2012, and 2016. As a conclusion, it is observed a progressive change of the utilization of the Colombian energy resources, favoring the use of electricity and natural gas instead of firewood, in agreement with the development from a rural to an urban nation, where most of the population is densely concentrated in large cities (>1 million inhabitants). The role of the transportation sector as the dominant sector in the energy mix in the last decades also follows the growing dependence of the country on the fossil fuels, whereas other renewable resources remains unused in industrial and residential sectors. These results will help in the decision-making of the future projects of energy planning and government policies directed towards a better utilization of the available energy and economic resources via the integration of advanced energy conversion technologies, more stringent environmental policies and more conscious practices of exergy consumption.

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