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Relational Analysis of the oil and gas sector of Mexico: Implications for Mexico's Energy Reform.

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Abstract

This paper describes a novel tool-kit to analyze energy systems in relation to the bio-economic and environmental performance of society. It is illustrated with data from the oil and gas sector of Mexico. The approach combines relational analysis (as developed in theoretical biology) and Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM). It integrates two non-equivalent views of the functioning of the oil and gas system starting from the identification and description of the relations between functional and structural elements. The metabolic pattern of the energy system is described as a sequential pathway generated by different functional elements (e.g., extraction, refining, transportation), each of which is made up of different structural elements (e.g., plants adopting different extraction techniques, diverse types of refineries, different methods of transportation), and operating at a given level of openness (imports and exports). The relations found over the elements of the energy system are described both in functional terms (what/why) and in spatial terms (where/how). The policy relevance of the information generated is discussed in relation to the Mexican Energy Reform.

Keywords: MuSIASEM, energy system, integrated assessment, relational analysis, Mexico's Energy Reform, oil and gas sector.

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1. Introduction

Energy has played an important role in human evolution, determining the pace of human activities within the economic process and the expression of complex societal functions [1–12]. One of the most important factors leading to the economic prosperity of contemporary society has undoubtedly been the abundant availability of cheap oil [4,8,13]. The concept of peak oil points at a pending crisis of the fossil-fuel-based economy and the need for readjusting to new biophysical constraints [14–16]. The consequences of peak oil are complex. Indeed, peak oil is not only about finding alternative energy sources, but also about readjustments of the economy and environmental impacts. While we can no longer rely on increasing supplies of fossil energy to power the growth of a carbon-based economy, there are many reasons to doubt that a quick and massive substitution of fossil energy with alternative energies is possible. Especially replacing oil as the main source of liquid fuels is a formidable challenge.

Current energy research and policies tend to focus either on increasing efficiency in the use of energy carriers in society (demand-side) or on the substitution of fossil fuels by renewable energy sources [8,21]. Relatively little research has been done on the biophysical performance of the oil and gas sector itself [20]. This is surprising as most oil-producing countries are not only progressively investing more money but also using more energy in fossil fuel exploration, extraction, processing and transportation [19]. The resulting growing level of emissions per unit of output from the oil and gas sector are expected to exacerbate future global carbon emission levels [20].

To fill this gap, this paper proposes an integrated assessment of the different processes taking place simultaneously at different hierarchical levels of organization in the network of energy transformations in the fossil fuel sector. Data of the Mexican oil and gas sector is used to illustrate the approach. The integrated analysis is obtained by combining two non-equivalent views (structural and functional) across different levels of analysis. The different functional elements of the sector are characterized using the concept of "processor"; the structural parts are characterized by the metabolic pattern of inputs and outputs for different typologies of technologies or regions in spatial terms. In addition, variables belonging to different dimensions of analysis are included in the analysis, while also differentiating between different types of energy qualities. Quantitative storytelling is employed to contextualize numbers in relation to energy policy. Our approach reflects the biophysical costs of the oil and gas sector and does not consider the prices of oil and gas in the market. We think that this is essential for a robust analysis that helps to understand the energy sovereignty of a country, given the volatile and unpredictable prices of oil in the market [17,18].

The Mexican oil and gas sector represents an interesting case to illustrate the approach. Mexico is one of the largest producers of oil and petroleum liquids in the world. Half of the oil domestically produced is currently exported. In 2015, the oil and gas sector of Mexico generated almost 5% of the GDP and 33% of public revenues [24]. However, since 2004 Mexico's oil & gas production has been steadily decreasing due to a decline in the productivity of the Cantarell oil field. Current energy reform, ending the 75-year-old state regulation, has opened Mexico's oil and gas market to private investors. One of the main aims of this reform is to increase the production of oil & gas through private investment [21,25]. At the same time, Mexico's climate policy must be addressed as PEMEX, the Mexican oil state company, is among the top ten fossil fuel producer's emitters in the world [26,27].

2. Methodology

2.1. Theoretical pillars

The proposed approach combines Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) [10,28–31] with principles of relational system analysis [32–35]. MuSIASEM is a logic of accounting based on concepts derived from bio-economics and complex systems theory [10,36]. It keeps congruence over quantitative assessments across different compartments (sectors) of society at various hierarchical levels of organization and combines non-equivalent descriptions of a given complex system [10,28,31].

Relational system analysis was first introduced by Robert Rosen. In his book "Life Itself" Rosen described relational theory of systems as: "How any System is organized to the extent that it can be analyzed into or built out of constituent components. The characteristic relationships between such constituent components, and between the components and the System as a whole, comprise a new and different approach to science itself, which we may call the relational theory of Systems" [37]. Hence, relational system analysis describes systems as patterns of expected relations over their structural and functional elements developed to fulfill a specific purpose. Relational analysis can be applied to adaptive metabolic networks capable of self-reproduction and self-maintenance, such as social-ecological systems [38]. In this case the emergent property of the system is the ability of the different constituent components to express a functional whole capable of reproducing itself and this emergent property gives the meaning and defines the identity (purpose) of the constituent components [38]. In human-made systems (e.g., society) the final cause is given by humans, and therefore the identity of the system is associated with the definition of a goal (what the system is expected to produce).

2.2. Relational analysis of energy systems

According to the principles of relational analysis the performance of the oil and gas sector of a given country does affect and, at the same time, depends on the role it is expected to play in the rest of the economy. The oil and gas sector is shaped by: (i) external constraints determined by boundary conditions, that is, the availability and quality of natural resources used as primary energy sources; (ii) internal constraints, imposed by the specific requirements of the other economic sectors, in terms of what energy carriers (both in quantity and quality) the oil and gas sector is expected to supply; and (iii) the technological capacity inside the energy sector. For energy systems relational analysis requires the integration of two non-equivalent representations: (i) the functional view identifying and describing the relations that functional elements have among themselves and with the whole to which they belong; (ii) the structural view identifying and describing the relations between functional elements and structural elements within a given spatial context [38].

Four functional components can be distinguished in the oil and gas sector that jointly fulfil its expected role: the extraction system, the transportation system, the refinery system, and the final distribution. To express their expected function, each of these functional components is made up of structural elements (Figure 1).

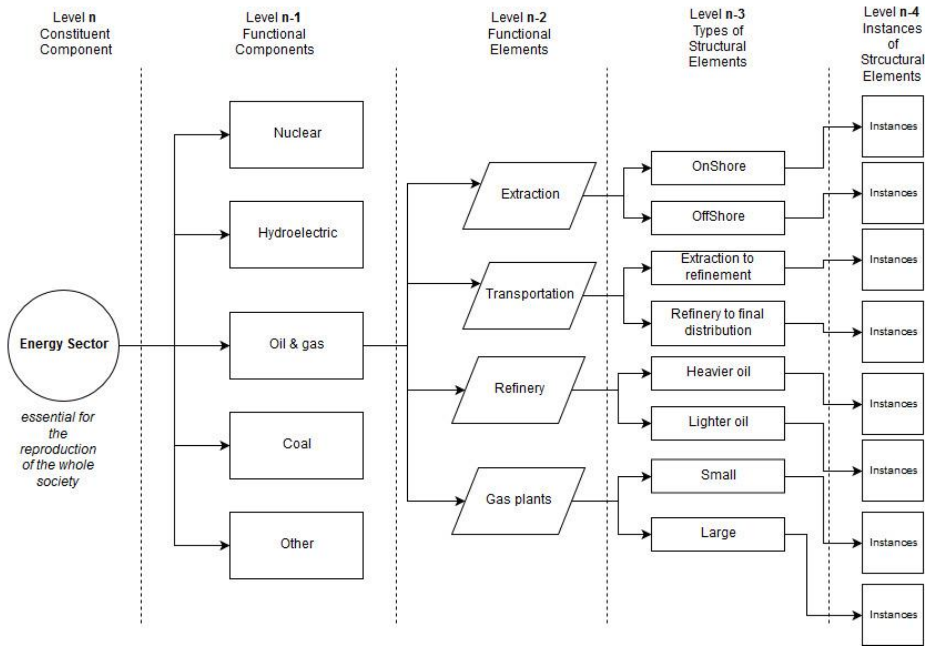

Figure 1: The relation over the distinct categories used to organize the quantitative characterization of the performance of the oil and gas sector.

Within this framework the metabolic pattern expressed by the gas and oil sector can be described as a sequential pathway generated by the different functional elements (e.g., extraction, refining, transportation), each of which is made up of different structural elements (e.g. plants adopting different extraction techniques, diverse types of refineries, different methods of transportation) located in space.

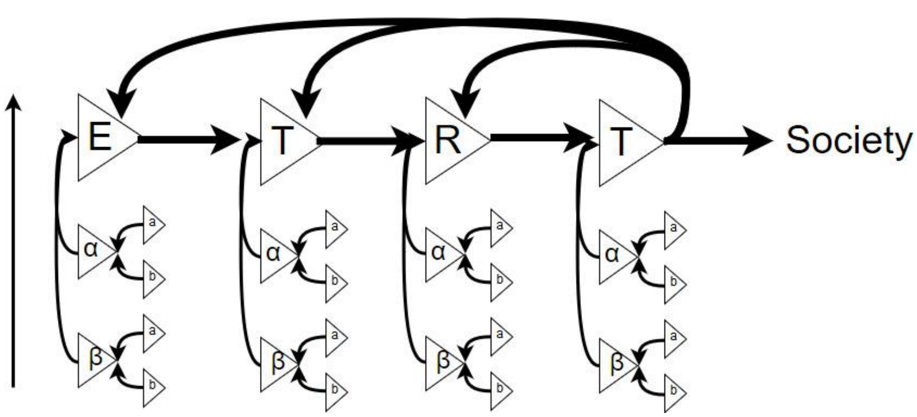

Figure 2: Structure and scaling of the oil & gas sector pathway. As described in the figure, the pathway is interlinked between the different nodes. E=Extraction, T=Transport from extraction to refinery or transport from refinement to consumption, R=Refinement. The pathway is scaled up from the structural elements (a, b) that conform the different functional nodes (α, β).

Note that the sequential metabolic pattern in the functional view (extraction → transport → refining) is not linear when considering the flows over structural elements in the structural view. Realizations (instances) of structural types are always associated with a location in space. For instance, specific refineries are located in specific regions. Therefore, depending on the geographic location of the structural elements operating in the oil and gas sector, the organization of the expression of the various functions can be done in diverse ways. In fact, in Mexico the operations of the gas and oil sector are realized through several different combinations of functional and structural types (functional type of refinery linked to a structural type of refinery, Figure 2). This is important for the scaling up of the different processes resulting in the whole metabolic pattern.

2.2.1. Functional elements

Each of the functional parts is described using "processors" (Figure 3), which are sets of data arrays that contain information about the profile of inputs (production factors, including resources under human control and resources from the environment) and outputs (the specific product as well as the pollution product of the studied process) associated with the process. For example, what is the function of the refineries that process heavy oil versus that of the refineries that process light oil, while in the structural part we can see in a synthetized way what is the difference in performance between two different instances.

It is important to differentiate between these two elements as many analyses only focus on one of them, losing information about the why, the what, the how and where the system works.

2.2.2. Structural elements

Structural elements describe the performance and the location of each instance of the system. The metabolic characteristics of these nodes are described both in extensive and intensive terms. On the one hand the extensive variables are measured in the conventional way without scaling per unit of throughput or per unit of fund element. Intensive variables on the other hand are measured by scaling a flow by unit of throughput or by unit of fund element. The intensive variables permit to compare inside nodes or across nodes because they are scaled by the same unit. For example, a way to compare between refineries would be by comparing the amount of energy used per unit of oil processed. Or in the case of comparing across nodes, it would be the amount of energy employed or emissions generated per unit of oil processed, extracted or transported.

2.2.3. *The concept of "processor"*

The semantic analog of the "processor" of energy systems is the enzyme for biochemical systems or the production function for economic analysis. In relational analysis it is a profile of expected inputs and outputs associated with the expression of a specific function. The processors of the functional elements of the energy system can be either scaled-up to describe the metabolic pattern of the system as a whole, or scaled-down by considering the characteristics of its lower-level parts (i) the processor provides information that makes it possible to carry out a bioeconomic performance, because it mixes together biophysical variables that are relevant for both economic, technical and ecological analysis, and (ii) the processor due to its epistemological ambiguity makes it possible to transfer information across assessments referring to instances, structural types, functional types and the whole.

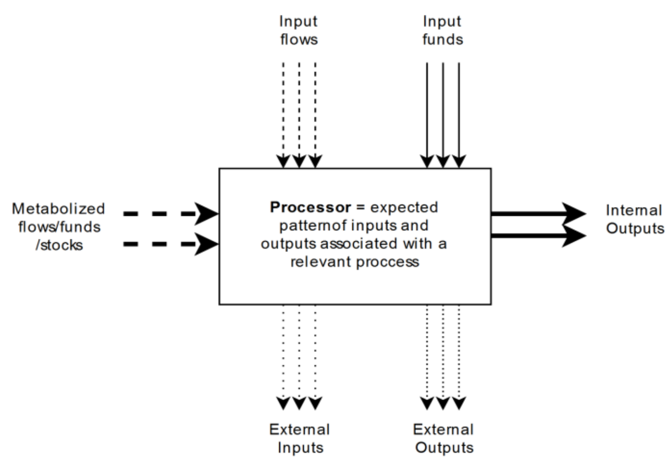

Figure 3: Processor description. The data array structure of the processor defines an expected mix of inputs and outputs associated with a specified process linked to the expression of a given task.

2.3. Data sources and organization

Most of the data presented here was obtained from PEMEX (Mexican Oil State Company) through use of the National Transparency System of Mexico (SNT), as the required data is not readily available in common databases. Other sources were the Institutional Database from PEMEX and the Energy Information System from SENER (Mexican Energy Secretariat).

The data was organized by structural and functional elements as shown in Figure 4.

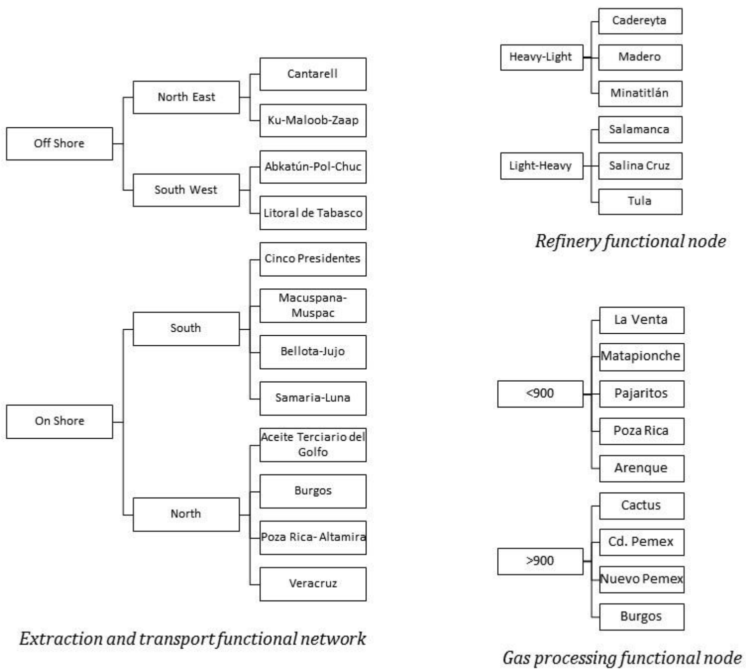

Figure 4: Structural elements of the functional nodes extraction and transport, refinery, and gas processing

3. Results

3.1. Extraction

Mexico obtains most of its oil from offshore extraction, from the North-East region where most of the heavy oil is extracted, most of the CO_2 is emitted by gas flaring and most of the energy for extraction is employed in absolute terms (Figures 5 and 6, and Table 1). The South-West region seconds the North-East in extraction terms. In this region, most of the Mexican light and superlight oil is extracted. The third producer region is the South. It produces the highest quantities of superlight oil in Mexico and demands the highest labor input. The North is the fourth oil-producing region. It has the second largest CO_2 emission per unit of oil extracted, and the highest ratio of labor invested per energy extracted (Table 1).

Most of the gas produced comes from onshore extraction, notably from the North region.

The South region has the highest ratio energy consumed per energy extracted but its ratio CO_2 emission per energy produced is the second smallest. The North-East region has the highest ratio of CO_2 emitted per energy extracted. The South-West region has the smallest ratio CO_2 per energy extracted.

In resume, the offshore regions produce more oil, in specific light and heavy, while the on-shore regions produce more superlight oil and gas. Offshore extraction emits more CO_2 to the atmosphere compared to onshore productions which have a bigger labor per energy and energy consumed per energy obtained ratios. Offshore areas have associated gas while in the onshore areas the non-associated gas increases. The amount of gas that is burned is greater in these areas than in onshore areas due to the poor performance in the separation of oil and gas. This has environmental and strategical consequences given that enormous amounts of gas are burned.

Onshore areas have more gas than oil, so they have another functional state in the system and different extraction tactics.

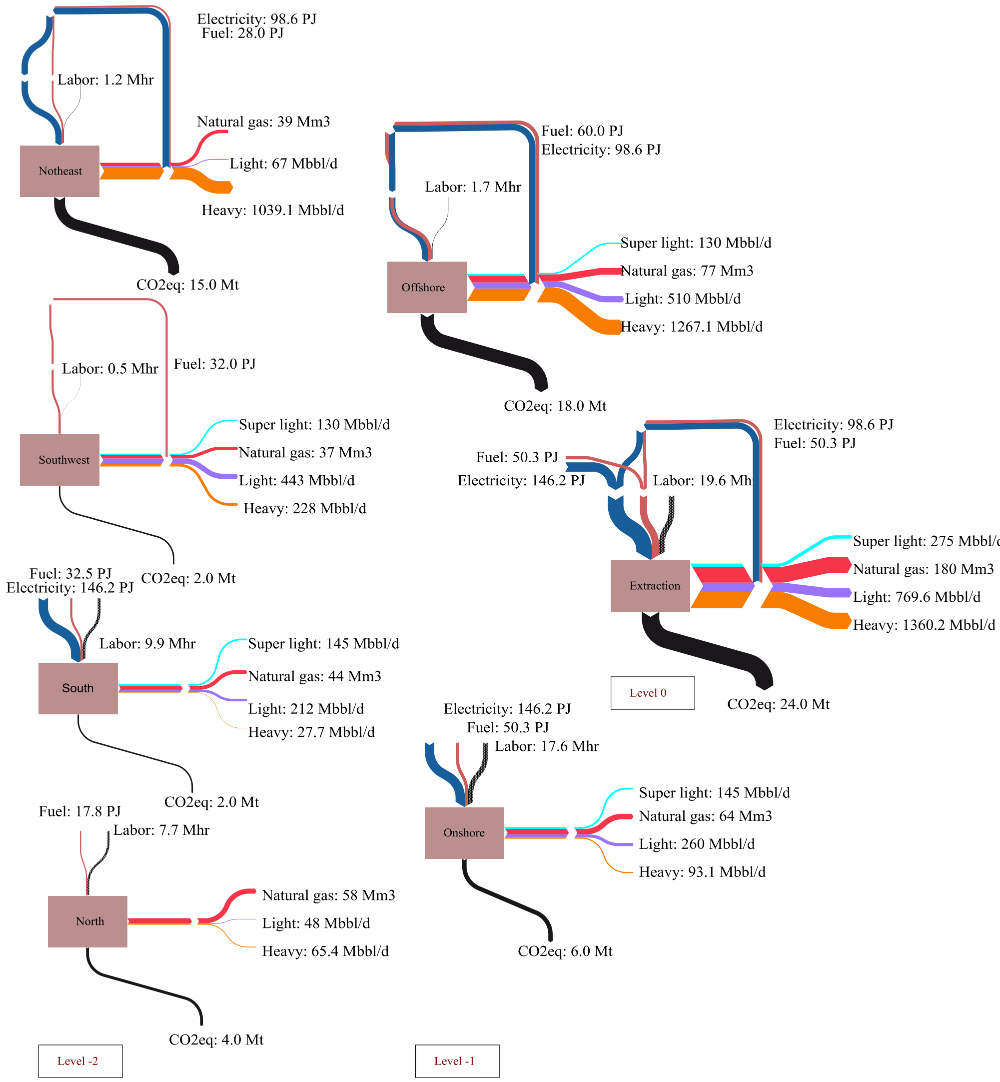

Figure 5: Functional node showing the scaling of extraction regions.

Table 1: Extraction system (Structural information).

Level 0 Extraction system				
Level -1 Extraction zones	**Offshore**		**Onshore**	
Level-2 Regions	**NE**	**SW**	**N**	**S**
Extensive variables				
Gross Energy Consumed (PJ)	126.58	32	17.82	178.66
Labor (Mhr)	1.2	0.48	7.7	9.9
CO_2 (t)	$1.58x10^7$	$2.70x10^6$	$4.20x10^6$	$2.32x10^6$

Gross Energy Extracted (PJ)	3059	1924	1046	1482
Intensive variables				
Labor/Gross Energy Extracted (10^3 hr/PJ)	0.4	0.2	0.7	0.7
CO_2/Gross Energy Extracted (t/PJ)	$5.15x10^3$	$1.40x10^3$	$4.01x10^3$	$1.57x10^3$
Gross Energy consumed/Gross Energy extracted (PJ/PJ)	0.04	0.02	0.02	0.12
Quality of the Energy consumed				
% Fuel	22%	100%	100%	18%
% Electricity	88%	0%	0%	82%
Source of electricity	Self-generated			grid

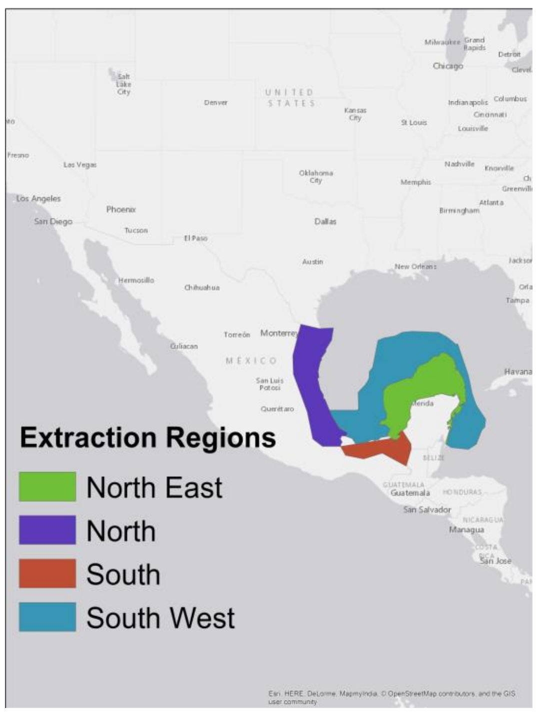

Figure 6: Regional division of oil and gas extraction systems

3.2. Refining

The definition of functional nodes in the refinery sector is based on whether they process predominantly heavy or light oil as the relative technologies employed require distinct types of fuel for processing. Refineries that process predominantly heavy oil require more dry gas and natural gas for processing. Refineries that process more light than heavy oil use more heavy oil, pet coke and steam. Note that the output of the refinery system not only consists of energy, but also other products destined for the building and manufacturing sector, the agricultural sector and the chemical industry (Figures 11 and 7).

Refineries that predominantly process heavier oil require more energy inputs and labor and emit more CO_2 to the atmosphere compared to refineries that predominantly refine light oil (Table 2). Refineries processing lighter oil produce most of the electricity required by cogeneration. In many cases, the surplus is sent to the grid.

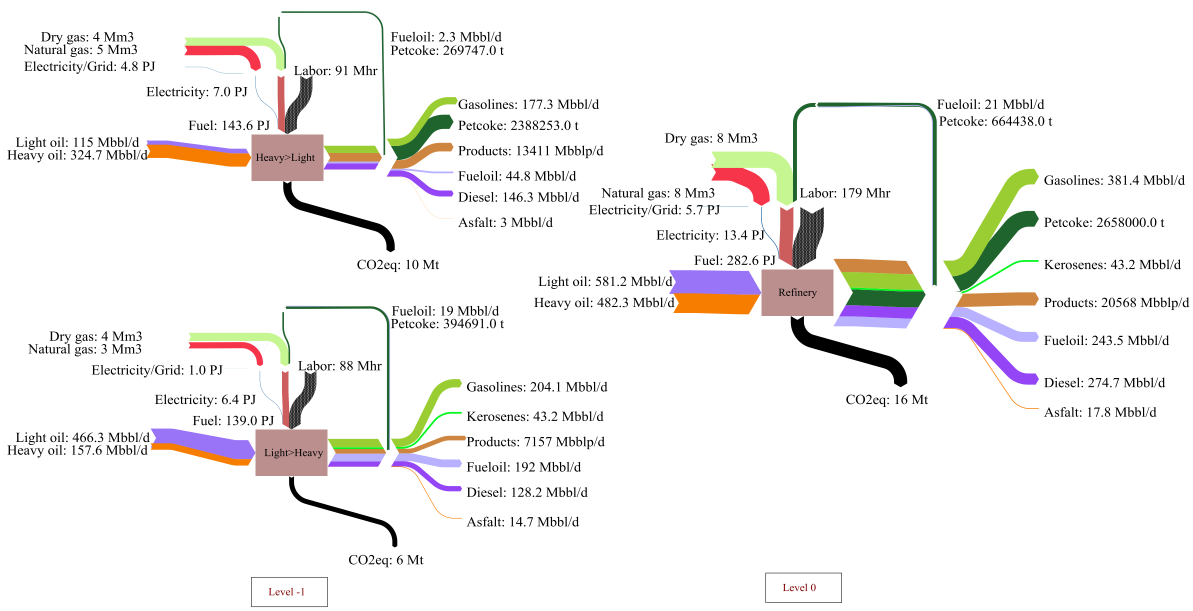

Figure 7: Functional description of the refinery system, including quality and quantity of energy inputs, labour input, and energy and non-energetic outputs.

Table 2: Refinery system (structural information).

Level 0 Refinery system		
Level -1 Refineries	>heavy	>light
Extensive variables		

Gross Energy Consumed (PJ)	151	145
Labor (Mhr)	91	88
CO2 (t)	1.04×10^7	6.11×10^6
Gross Energy Processed (PJ)	1675	1987
Intensive variables		
Labor/Gross Energy processed (10^3 hr /PJ)	54	44
CO2/Gross Energy processed (t/PJ)	6.19×10^3	3.08×10^3
Gross Energy consumed/Gross Energy processed (PJ/PJ)	0.09	0.07
Quality of the Energy consumed		
% Fuel	95%	96%
% Electricity	5%	4%
Source of electricity	Grid	Self-generated
Power capacity		
Power capacity (MMbd)	750	890
% Utilization factor	59%	70%

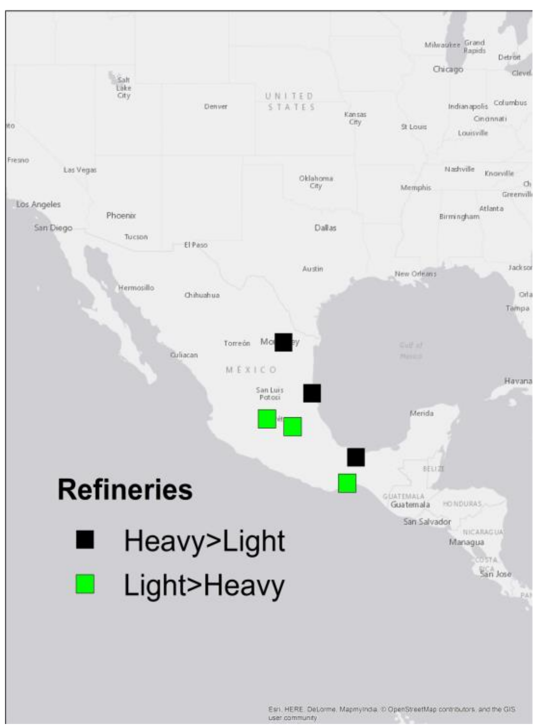

Figure 8: Refinery system (Spatial structural information).

Refineries predominantly processing heavy oil operate at 59% of their capacity (utilization factor 0.59); those that process predominantly light oil at 70% (Table 2).

3.3. *Gas processing*

The energy carriers obtained in gas processing are gasolines, ethane, gas LP and dry gas. Small gas processing plants produce proportionally more ethane than the bigger gas processing plants (Figure 9). Larger gas plants require less labor per energy processed than smaller plants but consume more energy and generate more CO_2 per energy processed than smaller plants (Figure 10).

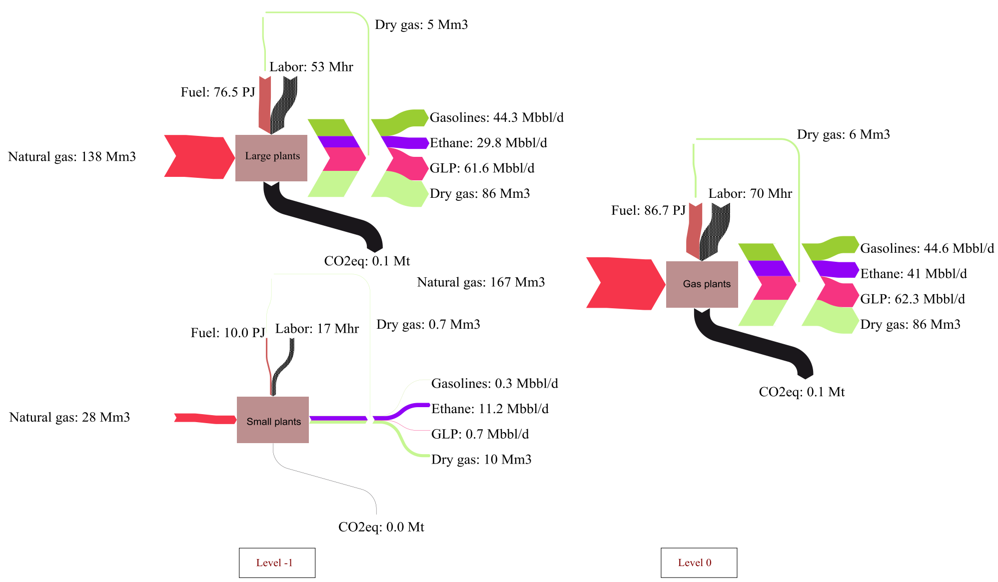

Figure 9: Functional description and scaling of the gas processing system including the quality of the energy inputs and energy and non-energetic outputs.

Table 3: Gas processing plants (structural information)

Level 0 Gas processing system		
Level-1 Gas plants	**>25x10^6 m^3**	**<25x10^6 m^3**
Extensive variables		
Gross Energy Consumed (PJ)	77	10
Labor (Mhr)	53	17

CO_2 (t)	$8.79x10^4$	$1.38x10^3$
Gross Energy processed (PJ)	1883	394
Intensive variables		
Labor/Gross Energy processed (10^3 hr/PJ)	28	43
CO_2/Gross Energy processed (t/PJ)	47	4
Gross Energy consumed/Gross Energy processed (PJ/PJ)	0.04	0.03
Quality of the Energy consumed		
% Fuel	100%	100%
Power capacity		
Power capacity	$138x10^6$ m^3	$34x10^6$ m^3
% Utilization factor	69%	59%

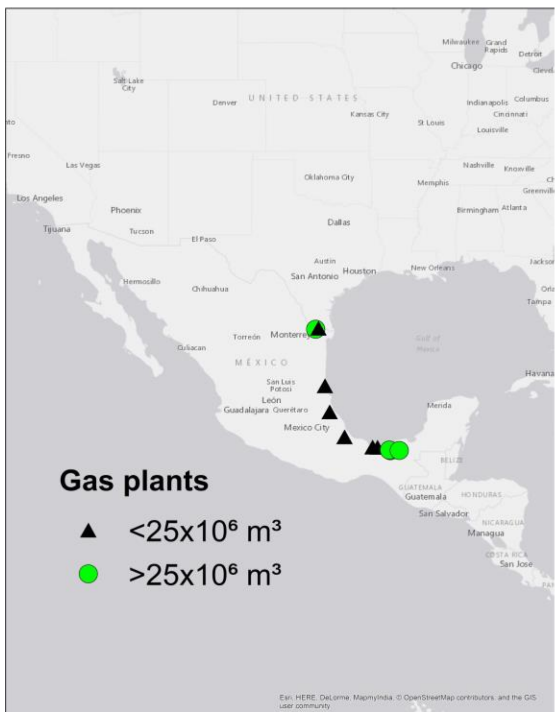

Figure 10: Gas processing system (Spatial structural information).

The bigger gas processing plants operate at 69% of their capacity utilization, the small processing plants at 59% (Table 3).

3.4. Transport

3.4.1. Transport from extraction regions to refineries and gas processing plants

Transport in offshore regions emits more CO_2 in both extensive and intensive terms. The North-East region demands more labor in absolute terms, but in terms of labor input per unit of energy processed the onshore regions are most demanding. The North region spends half of its energy in transport. This is to be expected given the huge area of this region (Table 4).

3.4.2. Transport from refineries and gas processing plants to final consumption

60% of the oil and gas products is transported by pipelines, 36 percent is transported by boats, and the rest by terrestrial transport (in this analysis terrestrial transport is omitted given the small number of products transported this way 4%). Pipelines are less labor demanding but are more energy intensive and emission intensive than ships (Table 5).

Table 4: Transport system 1 (Structural information).

Level 0 Transport from extraction to processing				
Level -1 Extraction zones	**Offshore**		**Onshore**	
Level -2 Regions	**NE**	**SW**	**N**	**S**
Extensive variables				
Gross Energy Consumed (PJ)	28	5	25	0.23
Labor (Mhr)	2	1	2	2
CO_2 (t)	$1.76x10^6$	$9.40x10^5$	$6.32x10^2$	$4.90x10^1$
Gross Energy Transported (PJ)	3014	2008	1046	1463
Intensive variables				
Labor/Gross Energy Extracted (10^3 hr/PJ)	1	0.3	2	1
CO_2/Gross Energy Extracted (t/PJ)	585	468	1	0
Gross Energy consumed/Gross Energy extracted (PJ/PJ)	0.01	0	0.02	0.0002
Quality of the Energy consumed				
% Fuel	100%	100%	100%	100%

Table 5: Transport system 2 (Structural information).

Level 0 Transport from processing to consumption		
Level -1 Technologies	**ships**	**pipelines**
Extensive variables		
Gross Energy Consumed (PJ)	73×10^{-5}	12
Labor (Mhr)	12	0
CO_2 (t)	2.62×10^{5}	8.24×10^{5}
Gross Energy transported (PJ)	1281	2197
Intensive variables		
Labor/Gross Energy transported (10^3 hr /PJ)	0.0093	0
CO_2/Gross Energy transported (t/PJ)	204	375
Gross Energy consumed/Gross Energy transported (PJ/PJ)	57×10^{-8}	53×10^{-4}
Quality of the Energy consumed		
% Fuel	100%	100%

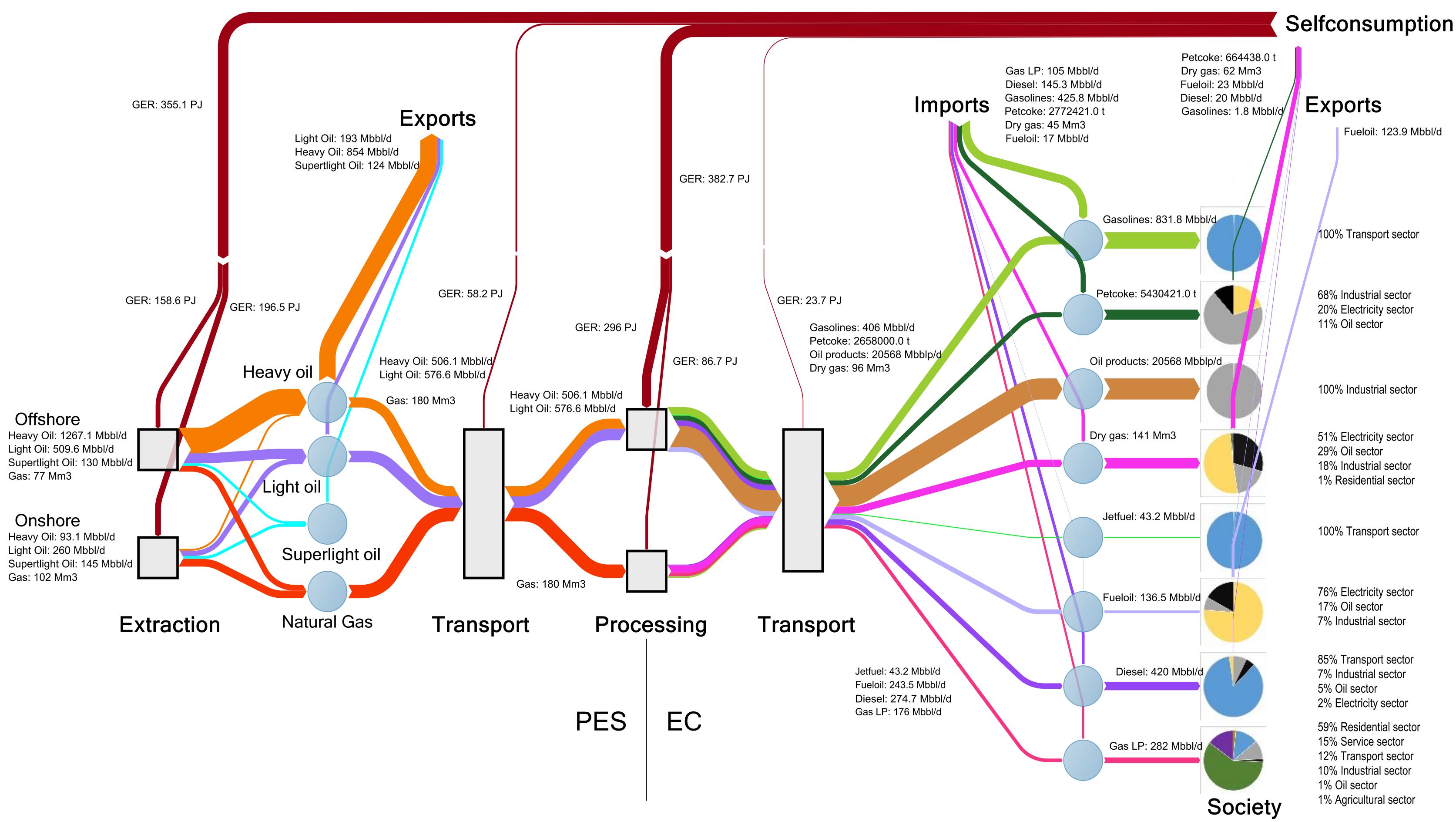
Selfconsumption
GER: 355.1 PJ
GER: 158.6 PJ
GER: 196.5 PJ
GER: 58.2 PJ
GER: 382.7 PJ
GER: 296 PJ
GER: 86.7 PJ
GER: 23.7 PJ
Offshore
Heavy Oil: 1267.1 Mbbl/d
Light Oil: 509.6 Mbbl/d
Superlight Oil: 130 Mbbl/d
Gas: 77 Mm3
Onshore
Heavy Oil: 93.1 Mbbl/d
Light Oil: 260 Mbbl/d
Superlight Oil: 145 Mbbl/d
Gas: 102 Mm3
Exports
Light Oil: 193 Mbbl/d
Heavy Oil: 854 Mbbl/d
Superlight Oil: 124 Mbbl/d
Heavy oil
Light oil
Superlight oil
Natural Gas
Heavy Oil: 506.1 Mbbl/d
Light Oil: 576.6 Mbbl/d
Gas: 180 Mm3
Heavy Oil: 506.1 Mbbl/d
Light Oil: 576.6 Mbbl/d
Gas: 180 Mm3
Gasolines: 406 Mbbl/d
Petcoke: 2658000.0 t
Oil products: 20568 Mbblp/d
Dry gas: 96 Mm3
Jetfuel: 43.2 Mbbl/d
Fueloil: 243.5 Mbbl/d
Diesel: 274.7 Mbbl/d
Gas LP: 176 Mbbl/d
Imports
Gas LP: 105 Mbbl/d
Diesel: 145.3 Mbbl/d
Gasolines: 425.8 Mbbl/d
Petcoke: 2772421.0 t
Dry gas: 45 Mm3
Fueloil: 17 Mbbl/d
Petcoke: 664438.0 t
Dry gas: 62 Mm3
Fueloil: 23 Mbbl/d
Diesel: 20 Mbbl/d
Gasolines: 1.8 Mbbl/d
Exports
Fueloil: 123.9 Mbbl/d
Gasolines: 831.8 Mbbl/d
Petcoke: 5430421.0 t
Oil products: 20568 Mbblp/d
Dry gas: 141 Mm3
Jetfuel: 43.2 Mbbl/d
Fueloil: 136.5 Mbbl/d
Diesel: 420 Mbbl/d
Gas LP: 282 Mbbl/d
100% Transport sector
68% Industrial sector
20% Electricity sector
11% Oil sector
100% Industrial sector
51% Electricity sector
29% Oil sector
18% Industrial sector
1% Residential sector
100% Transport sector
76% Electricity sector
17% Oil sector
7% Industrial sector
85% Transport sector
7% Industrial sector
5% Oil sector
2% Electricity sector
59% Residential sector
15% Service sector
12% Transport sector
10% Industrial sector
1% Oil sector
1% Agricultural sector
Society
Extraction
Transport
Processing
Transport
PES
EC

Figure 11: The complex metabolic pathway described in terms of functional elements. The different flows are transformed across the metabolic pathway from Primary Energy Sources (PES) extracted from the different reservoirs to Energy Carriers (EC) delivered to society. Data refer to Mexico.

3.5. Performance of the oil and gas sector as a whole

In this section the information describing the various functional elements of the system is combined to analyze the overall performance of the oil and gas sector in relation to both its functional components and its overall characteristics. Indeed, the oil and gas sector is a constituent component of society and its metabolic pattern must stabilize a complex network of pathways: the set of inputs used by the oil and gas sector and the set of outputs delivered to the rest of society. This is illustrated in Figure 11 for Mexico.

3.5.1. Analysis of the functional elements (across regions)

Considering the extensive variables (overall quantities per year), extraction is the most energy-consuming function, followed by refining, then gas processing and finally transportation (Figure 13). Considering intensive variables (quantity of input per unit of output), the most energy intensive system is refining, followed by extraction, gas processing, and transport from extraction system to processing. The least energy intensive system is transportation from processing to consumption.

With regard to labor, in extensive terms the functional element requiring more hours of work is refining, followed by gas processing, and extraction. Transport is the least demanding in this regard. In intensive terms, the same pattern is found, with refining being the most labor-intensive function and transport the least labor-intensive function.

With regard to emission, considering extensive variables the functional element that emits more CO_2 into the atmosphere is extraction, followed by refining, gas processing, and finally transport. Expectedly, this pattern is similar to that for energy demand. Transport from extraction to processing emits more CO_2 than transport from processing to end use. When using intensive variables, the most emission intensive functional element is refining followed by extraction, then by the transport system and finally by the gas processing system.

3.5.2. Whole system indicators

An integrated set of indicators characterizing the overall performance of the oil and gas sector can be obtained by summing the extensive variables (the quantities of inputs and outputs used by the processors describing the different functional elements). An example is provided in Figure 13. Note that the choice of these indicators can be done "a la carte" in relation to the specific policy problem considered at the moment of developing the analysis. In fact, when adopting relational analysis there is an impredicative relation between the framing of the issue (what is the question) and the characterization of the system in the analysis (what the relevant functional and structural elements are and what are the relevant inputs and outputs to be included in the assessments).

Figure 12: Representation of the entire system interconnected by the transport system.

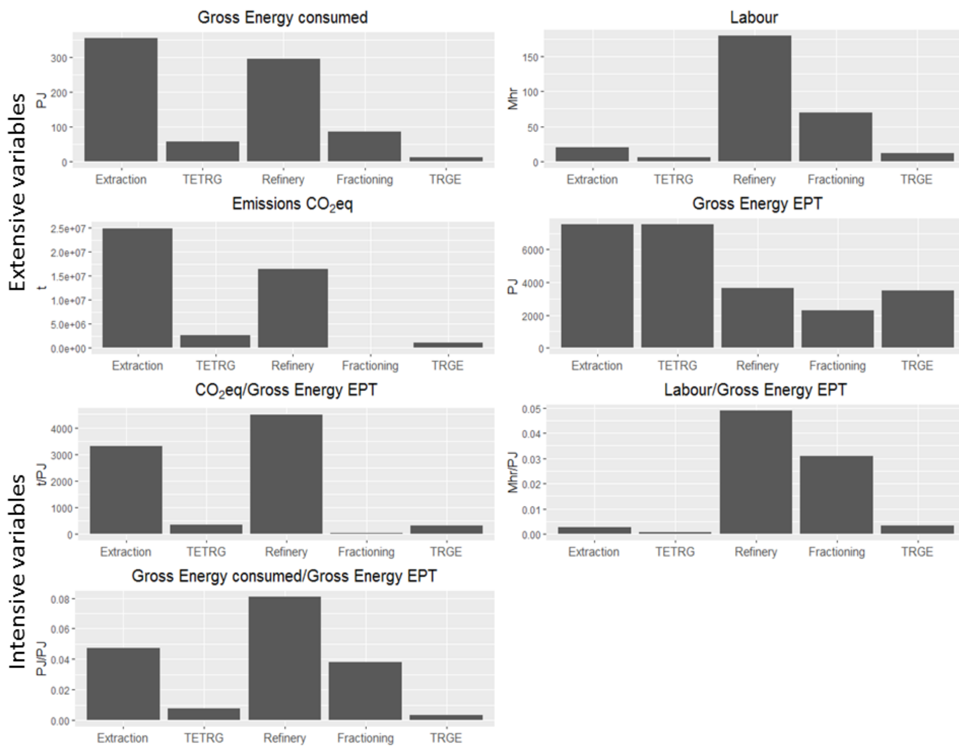

Figure 13: Example of indicators characterizing the bioeconomic performance of the whole oil & gas sector. TETRG=Transport from extraction to refineries and gas processing plants.

TRGE=Transport from refineries and gas processing plants to end use. EPT= Energy extracted, processed or transported. Data refer to Mexico.

3.5.3. *End-uses of the outputs of the oil and gas sector*

Almost all of the gasolines produced in the Mexican oil and gas sector are used in the transportation sector. Fuel oil is an undesired product (by-product) and within Mexico it is used as input for electricity generation, which results in massive amounts of CO_2 emitted into the atmosphere [39]. Almost all the fuel oil comes from the refineries that process lighter mixes of oil, and specifically from the Salina Cruz refinery that has an old configuration [40]. Fuel oil has less added value than other fuels such as gasolines and jet fuel, and as shown in the metabolic pathway half of the fuel oil produced is exported as such rather than being further processed into gasoline. Further processing of fuel oil would reduce the need for gasoline imports.

Gas is claimed to be the transition energy of the 21 first century [41]. However, note that in the Mexican supply system gas is tightly linked to oil because part of the gas is obtained from the same fields as oil. This is particularly true for the off-shore regions, where many of the infrastructures are the same for oil and gas extraction. Gas production cannot be uncoupled from oil in Mexico unless the fields from where the gas is extracted do not have oil associated or there is the possibility for independent processing and consumption.

Petcoke is majorly destined to the industrial sector (68%) and used to a lesser extent by the electricity sector (20%) and oil sector (11%). Petrochemicals are used in their majority by the industrial sector as inputs for processing, varying from cement industry, food, pharmaceutical, etc. Kerosene is demanded by the transport sector for airplanes. Fuel oil is demanded for the most part by the electricity sector (Figure 11), then by the industrial sector, the oil sector and the electricity sector. Most of the gas LP ends up in the residential sector, seconded by the service sector, then by the transport sector, industrial sector, oil sector and agricultural sector.

3.5.4. Imports and exports

Fifty percent of the gasolines are imported (Figure 11). Two thirds of the heavy oil are exported, almost all the superlight oil is exported and one fifth of the light oil is exported. Half of the dry gas is imported, one third of diesel is imported, and one third of LP gas is imported.

4. Discussion

It is impossible to check and study the performance of the oil and gas sector by using simple systems of monitoring and control in the form of input/output indices or simple ratios of investment that mix information of different qualities. An analytical tool kit informing policy must have an adequate power of discrimination to find relevant characteristics across different scales and different dimensions of analysis. This requirement of variety in the analysis has been neatly summarized in Ashby’s law of requisite variety [42] and was well known to the pioneers of energetics in the 70’s. When dealing with the analysis of complex energy systems one has to diversify the accounting of different energy forms associated with different processes carried out in the metabolic pathway in different places and at different times in relation to different types of inputs and outputs generated [43–45]. An effective energy analysis has to define an integrated set of indicators of performance and not just maximize input/output ratios applying naive definitions of efficiency [8].

The creation of a richer information space to characterize the performance of the energy sector, as proposed in this paper, guarantees that the process of decision making can be better informed. Indeed, the proposed approach allows an assessment of changes taking place in the different structural and functional elements of the oil and gas sector in relation to employment (labor), bio-economic costs, technical issues, regional development, and environmental impacts. Changes in lower-level components can be scaled-up to changes in the overall performance of the whole sector. Therefore, this type of analysis can anticipate trade-offs in policy discussions, such as the pros and cons of (i) exporting oil; (ii) producing and consuming oil domestically to support the different sectors of the economy; (iii) reducing emissions and environmental impact. The environmental implications (GHG emissions) of the exploitation of oil increasingly difficult to extract are particularly relevant in view of negotiating climate policies.

Mexico is currently modernizing its refinery system, incorporating electricity cogeneration and opening the system for new refineries. The information used to describe the performance of the energy sector should be able to inform a holistic discussion of the "whys" and the "hows" of this modernization. That is, Mexico should decide, based on a sound discussion, how to wisely use its finite resources of oil and gas in face of the trade-offs listed above. Can we characterize how the use of these resources is supporting the Mexican economy? What mix of products should be produced and consumed internally to support the development of the different sectors of the economy?

The dependency on importation is another factor essential for a discussion of the plan of modernization of refineries in Mexico. They, at the moment, not only do not produce the gasolines required by the economy but also are not operating at their highest utilization factor. A similar problem is seen for the gas processing plants.

When dealing with this type of problems, relational analysis of the metabolic pattern of society helps to establish a relation between the specific patterns of production (supply) of energy carriers (presented in this paper) and the specific patterns of end uses in the society. An energy end-use matrix uses the same logical approach to identify which type of energy products are used by the different sectors of the economy, how much, how and why [46,47]. In a future work, we will use the same approach to analyze the metabolic pattern on the consumption side: to identify which sectors and subsectors of the Mexican economy are using which type of energy products to do what. Indeed, to improve the performance of the economy in relation of the use of energy carriers, it is necessary to generate a holistic vision of the complete process of production and use of energy carriers in society.

Regarding the possibility of identifying and characterize the nature of specific problems associated with geographic location, most of Mexico's oil reserves are in the North-East off-shore region, which is the most emission-intensive region. Using the integrated analysis presented here it is possible to look for solutions to the problem represented by the fact that the emissions are potential energy lost by the gas flaring. This influences also the refinery systems as it determines the mix of oil that can be processed. Much of the gas flaring is due to the gas associated to oil, which must be burned to reduce the methane emissions. One possible transition away from the existing situation, without major changes in infrastructures, would be the generation of dry gas: it emits less, and it demands less energy than the refinery system. Perhaps some fuels can be replaced by dry gas in the industry. The analysis of possible scenarios would be more robust if could be checked in terms of relational analysis.

5. Conclusion

The relational analysis presented in this paper makes it possible to describe the bioeconomic performance of the oil and gas sector across different levels and dimensions of analysis. It establishes an analytical interface between the way (how) energy carriers are produced and how they are consumed in an economy. The resulting information space permits a holistic analysis of energy and climate policies in relation to different objectives and provides a variety of indicators useful for different purposes. A holistic vision of the complex interplay between energy supply and demand-side is currently missing both in terms of policy and scientific analysis [22,23]. The approach can equally well be applied to renewables.

With regard to the particular case of Mexico, the analysis shows that the direction of the Mexican Energy Reform is closely tied to the final cause of the oil and gas sector. Mexico should rethink the strategy of how to use its finite fossil energy resources and not only invest efforts in extracting more oil and gas and, in doing so, remaining stuck in business as usual. Given the volatility of the oil & gas prices Mexico should reconsider oil export and instead employ this resource in activities that generate more added value and create less dependence on the oil market.

Qualitative reforms are recommended in final consumption and in the oil and gas system itself. A reform in the refinery system could address the current dependency on gasolines imports and generate fuels with more added value than that of the residual fuel oil that is currently employed for electricity generation and resulting in excessive amounts of emissions. A reform in the transport sector diversifying the fuels employed would help reduce the demand of imported gasolines. The incorporation of diversified sources of electricity generation that include renewables would reduce the amount of fuel oil and natural gas employed and by this reduce the emissions generated by the fuel oil consumption and the dependency on natural gas importation.

Mexico should incorporate the PostCOP agenda into the Energy reform, given that PEMEX is at the top ten fossil fuel producer's emitters in the world, and that many of the emissions are simply due to inefficacy in some of the offshore extraction regions where the gas associated to the oil extracted is flared and where most of the heavy oil reserves are allocated.

This paper accomplishes its main objective: generate a holistic information toolkit useful for policy discussion.

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