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An integrated multi-scale approach to assess the performance of energy systems illustrated with data from the Brazilian oil and natural gas sector

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ABSTRACT

We apply Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to the performance of society's energy system, and illustrate our approach with data from the Brazilian oil and natural gas sector. Key features of MuSIASEM include the multi-scale property and use of grammars. The former builds on a dual definition of the energy system: functional components or (sub)sectors are described as aggregate energy flows (extensive variables) using top-down information from statistics, while structural components (plants, technologies) are described as unitary operations (intensive variables). Integrating descriptions, we can scale information across the energy system's complex hierarchical organization. Use of an energy grammar mandates the pre-analytical definition of accounting categories, primary energy sources and energy carriers; thermal (e.g., fuels) and mechanical energy (e.g., electricity), and a set of expected relations over the different energy forms. Our preliminary analysis shows that MuSIASEM effectively describes the required investment of energy carriers (in quantity and quality) and other production factors, such as labor, in society's energy sector.

1. Introduction

The energy sector is the 'motor' that powers all activities of modern society. A comprehensive understanding of its functioning is essential not only for deciding on internal energy policies (investments, subsidies), but also to elaborate more sustainable economic policies [26,47,48]. For this reason and because of the global crisis of the existing pattern of economic growth that cuts across the different dimensions of sustainability – ecological economic and social – it is becoming essential to rethink the way future economies will use energy in order to keep producing and consuming their goods and services [3,7,10,12,18,19,27,28,44]. To achieve these goals it is essential to develop more effective approaches to the integrated assessment of the performance of energy systems [19]. A contribution toward the achievement of new approaches to quantitative energy analysis is presented in this paper. The text of the paper is organized as follows: (i) Part 1 briefly discusses the existence of deep epistemological challenges that have to be addressed to improve the usefulness of the assessment of the performance of energy systems; (ii) Part 2 presents an example of application of an innovative accounting system based on the rationale of MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) to the oil and gas sector of Brazil, that avoids some of the pitfalls of conventional energy accounting; (iii) a short section of conclusions closes the paper indicating shortcomings of this application and the next steps in this line of research.

2. Assessing the performance of energy systems: an overview of epistemological conundrums

2.1. Basic problems with energy accounting

The accounting of quantities of energy (like any other accounting) requires the use of given units of measurement, such as the joule (J), kilocalorie (kcal), or kilowatt-hour (kWh). However, not

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necessarily energy quantities expressed in a common unit of measurement can be summed. No accountant will sum 100 US$ of profit, to 100 US$ of gross revenues, to 100 US$ of taxes, only because they are measured in the same unit: US$. In the same way, there are different energy forms that even if measurable in (or reducible to) the same unit – e.g. joules – cannot be summed because they are non-equivalent in their qualitative nature [19]. In particular there are two key distinctions that have to be considered when coming to the accounting of quantities of energy: (1) thermal energy vs mechanical energy – the qualitative difference between these two forms of energy is what generated the field of classic thermodynamics – i.e. how to study the conversion of quantities of thermal into mechanical energy and viceversa; and (2) primary energy sources versus (secondary energy) energy carriers. The acknowledgment of a qualitative difference between these two forms of energy is essential to discuss of energy security. In fact, according to the first law of thermodynamics, primary energy sources cannot be made by technical processes. They must be already available in the external world in order to have further energy transformations. When considering these two distinctions, we end up with (at least) four distinct categories that must be used in energy accounting. This is illustrated in Fig. 1 (after [19].

As regards the first distinction between thermal and mechanical energy, the qualitative difference between these two forms of energy was first pointed out by the pioneers of thermodynamics. The operation of a thermal engine clearly shows the difference in quality between 1 J of thermal and mechanical energy, as in this process we 'sacrifice' a larger quantity of J of thermal energy to obtain a smaller quantity of J of mechanical energy. In the same way, when producing Energy Carriers from Primary Energy Sources modern energy sectors sacrifice large quantities of thermal energy (joules in the form of fossil energy) to produce a smaller number of joules of electricity (a form of mechanical energy). It should be noted that also when transforming Energy Carriers into Energy Services this distinction remains essential: converters of energy carriers into useful energy are specific for these two energy forms: big airplane liners are not running on electricity, light bulbs do not run on diesel!

As regards the second distinction – primary energy sources vs (secondary energy) energy carriers – primary energy sources are defined as quantities of referring to forms of energy made available by processes beyond human control – examples are fossil energy, solar energy, and wind energy. Energy carriers (also called 'secondary energy') are forms of energy generated by processes under human control and powered by primary energy sources: e.g. 42 MJ associated with 1 kg of gasoline. This distinction it is important because the production of energy carriers requires: (i) the availability of primary energy sources (e.g. crude oil to be extracted); (ii) the availability of technological power capacity (e.g. technology needed to extract, transport and convert crude oil into fuels); (iii) the availability of human control (e.g. labor); and (iv) the availability of energy carriers to be used to power the activities required for their own production [19]. So the analysis of energy security can be divided in two different aspects [19]:

* when studying the existence of external limits we have to study the conversion of Primary Energy Sources into Energy Carriers. That is we have to analyze the relation between available Primary Energy Sources and available production factors (labor, technology and energy carriers used as inputs) in the energy sector;
* when studying the ability of delivering the expected energy services to the rest of society we have to study the conversion of Energy Carriers into End Uses. That is we have to study the quantity and the mix of production factors (labor, technology and energy inputs) required for achieving an expected set of energy services (the useful tasks associated with socio-economic activities) in the various sectors of the economy.

The need of using at least four distinct categories of energy accounting is in general ignored in the handling of quantitative characterization of energy flows. For example, if we assess the total

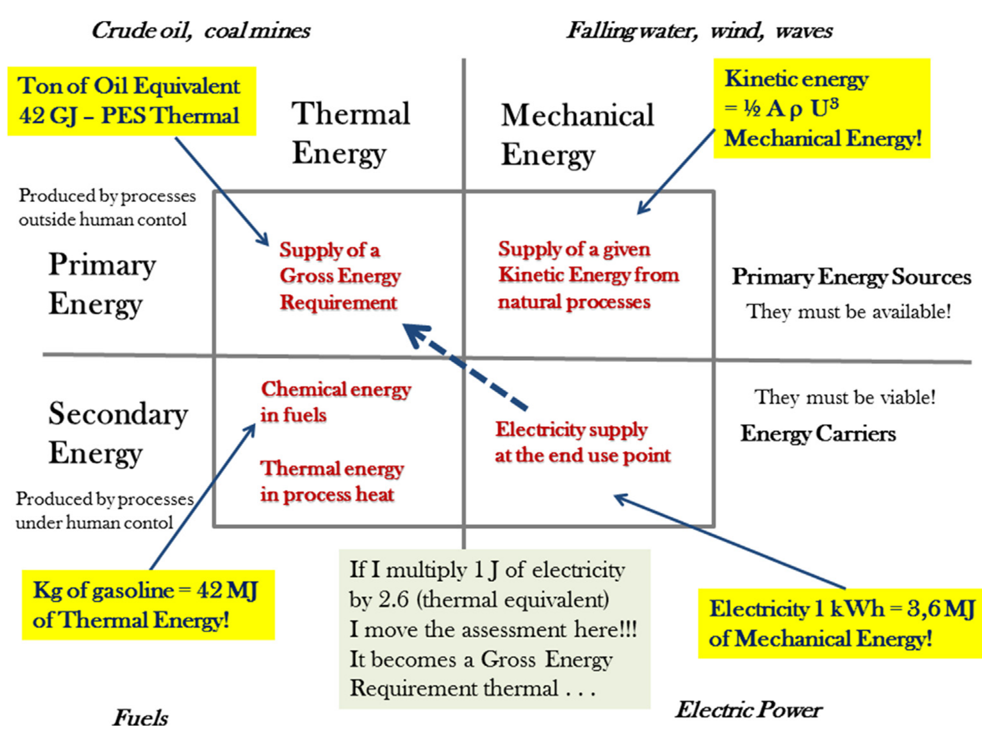

Fig. 1. Example of categories of energy accounting generating non-equivalent assessments.

energy consumption of a country in Primary Energy Equivalent – e.g. Tons of Oil Equivalent – this assessment will not be useful either to assess the tons of CO_2 emitted or to study the efficiency of electric appliances (this would require a local assessment done in kWh of electricity – secondary energy). Moreover, different choices of the equivalence criterion used to aggregate these different energy forms implies that different statistical sources (EIA, Eurostat, BP, the US IEA) provide different assessments of energy flows per country [19]. The same problem is faced when adopting simplified protocols of accounting aimed at defining the quality of energy sources – e.g. the EROI, the Energy Return On the Investment [24,26,34,40]; see also the special issue of the Journal Sustainability: [25]. The proposed indicator – a simple ratio obtained by dividing the joules supplied by the joules consumed in generating the supply – necessarily miss key information (for a more detailed discussion see Ref. [19] about: (i) the different quality of the inputs (the "energy investment" is a mix of mechanical and thermal energy and a mix of primary energy sources and energy carriers); and (ii) the scale of the process (a ratio is a simple number not providing any information about the quantity of energy associated with the size of process). In alternative SANKEY diagrams, in which the quantities of different types of energy forms are kept separated (http://www.iea.org/sankey/), avoids the loss of information associated with the aggregation of quantities belonging to non-equivalent categories of accounting, but ignore the mechanisms (the characteristics of the processes) determining the conversions over the different flows. Therefore, to obtain a sound characterization of the performance of an energy sector one has to use: (i) a taxonomy of accounting categories making it possible to keep the distinction between different energy forms (Fig. 1); and (ii) a set of expected relations making it possible to integrate qualitative differences – e.g. input/output ratios expressed in terms of intensive variables – and quantitative assessment – e.g. the throughput expressed in terms of extensive variables – associated with the identity of the network of energy transformations. In relation to the taxonomy of accounting categories, energy forms under human control have to be accounted in terms of joules of *energy carriers* keeping separated the accounting of joules of electricity and joules of fuels, whereas energy forms outside human control have to be accounted in terms of *primary energy sources*. This separate accounting requires the use of data arrays rather than simple numbers.

2.2. Basic problems with multiscale accounting

When considering the performance of a subsystem of the energy sector – e.g. the oil and gas sector – we have to assess inputs and outputs across a chain of functional compartments. At this level of analysis, we are dealing only with the domestic supply of oil and gas not including the effect of imports and exports. A simplified example of this analysis is given in Fig. 2. In this case we consider the oil and gas sector as made of four functional compartments: (i) Extraction; (ii) Transport 1 (to the refinery); (iii) Refining; (iv) Transport 2 (to final users). When considering the inputs getting into these compartments we have:

* *on the top of the figure* three types of inputs required to express these functions: (i) electricity; (ii) fuels; and (iii) labour – required to express the process under human control;
* *on the bottom of the figure* two type of inputs: (i) crude oil; and (ii) natural gas (primary energy sources) – required to operate the chain of transformations.

If we try to calculate output/input ratios – the technical coefficient of transformations expressed over unitary operations – to describe the qualitative characteristics of the different transformations taking place in these functional compartments we can immediately recognize the predicament associated with the issue of scale mentioned earlier. Functional types (transport of the crude from the block of extraction to the refinery) are defined at a higher hierarchical level than structural types (the specific instances of technology used to express such a function). That is a functional type may include the operations of several different structural types. For example, the function of extraction can be carried out by two different types of structural plants for extraction: on-shore and off-shore plants. These different typologies of structural types imply the expression of different technical coefficients. The same applies to the function "Transport 1" to the refinery. Crude oil and gas can be transported (same functional type determining the compartment transportation) in pipelines, ships/barges, and trucks (three structural types mapping onto the same function). Clearly, these different methods of transportation imply a quite heterogeneous set of technical coefficients (requirement of inputs) for the same quantity of throughput.

It is possible to define for each of the structural types associated with a functional type an array of data indicating how much labor, how much electricity and how much fuels are required by the structural type per unit of throughput processed. When expressed in biophysical terms this array describes the characteristics of the technical coefficients of the plant expressed in terms of unitary operations – the identity of the structural type. At the same time it is possible to define for each of the functional type an array of data indicating how much labor, how much electricity and how much fuel are required to express the given function in a given socio-economic system. When expressed in economic terms this characterization would be called an aggregate function of production for the sector under consideration (then it should require also the specification of the power capacity – the technical capital used in the process). As discussed earlier the performance of the four functional units (and the resulting performance of the whole oil and gas sector) does not depend only on the characteristics of the technical coefficients associated with the structural types used in the lower level. That is, even if we know the technical coefficients of the different technologies operating in the oil and gas sector we need additional information in order to be able to "scale-up" this data to assess first the performance of the functional types and then the performance of the whole gas and oil sector. In section 3 we show what type of additional information is needed and what type of accounting is needed to generate such a scaling.

2.3. How to assess the level of openness of the energy sector

The energy sector is an interface between the internal consumption of energy carriers inside the society and the processes determining the availability of primary energy sources outside the society. For this reason, it is important to be able to "visualize" the role of the domestic supply in determining the energy security of a country by defining in quantitative and qualitative terms the various functional and structural elements making up the network of energy transformations. By adopting the MuSIASEM approach this visualization can be obtained by developing an energy grammar [17,19]. In Fig. 3 we illustrate an example of a simplified energy grammar useful to analyze the relation between the energy sector and the 'rest' of society. This grammar distinguishes between: (i) quantities of energy associated with *primary energy sources* (energy forms beyond human control) exploited within the boundaries of the system considered: domestic supply; (ii) quantities of energy associated with *primary energy sources* (energy forms beyond human control) imported from outside; (iii) quantities of energy associated with *energy carriers* (secondary energy

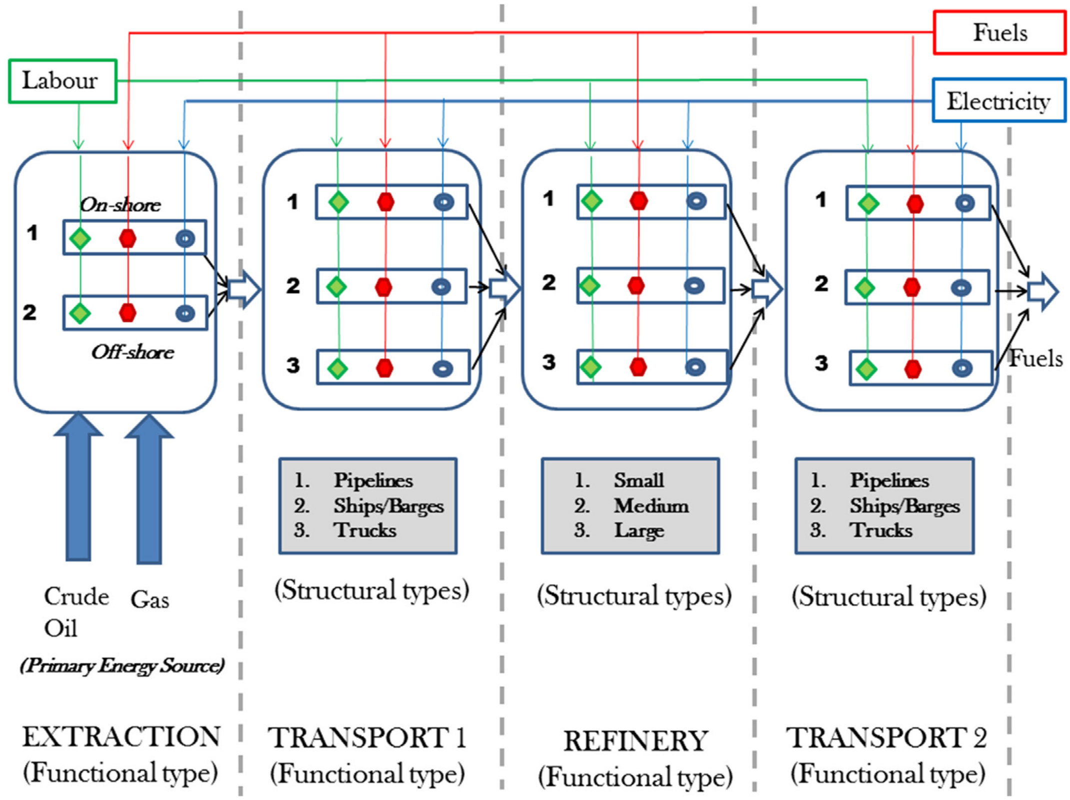

Fig. 2. A schematization of inputs, outputs and throughputs in the oil and gas sector.

forms under human control) produced inside the system; and (iv) quantities of energy associated with *energy carriers* (secondary energy forms under human control) imported from outside. The latter two quantities are assessed in terms of both thermal (fuels) and electrical (mechanical) energy. The grammar makes it also possible to illustrate how the energy carriers made available to the society (either because of domestic supply or import) are eventually used in the form of specific *end-uses* by the various sectors of society, including the energy sector itself, and/or exported.

The grammar illustrated in Fig. 3 allows us to describe: (i) the level of openness of the system (in its interaction with the context) through imports and exports in relation to domestic production and gross consumption; and (ii) the network of transformations taking place within the system through gross throughput (overall flow), the losses, and the net throughput in each one of the functional compartments, individuating in this way the fraction of the gross energy input needed for the energy sector itself (the hypercycle, e.g., energy carriers used to make energy carriers). Thus, in this approach the metabolic pattern is characterized by combining two complementary views: the *external* view (posing limits on the transformation of PES into EC) and the *internal* view (determining the options of conversion of EC into EU).

In the external view (left side of Fig. 3), we can describe and assess quantities of energy in terms of primary energy sources, which allows us to analyze the severity of external constraints. We focus on (i) (lack of) availability of natural resources (determined by processes beyond human control) that limit the domestic supply; and (ii) processes taking place outside the system's boundaries that determine available imports (e.g., the cost of the imports).

In the internal view (on the right side of Fig. 3), we can focus on the assessment of quantities of energy in terms of energy carriers (thermal and mechanical energy) and analyze the factors that determine the internal constraints. Here we study the processes under human control that take place within the boundaries of the system (e.g., the technical coefficients of individual processes, availability of production factors) and the fraction of the total energy transformations that is required for the operation of the energy sector itself (the energy carriers consumed to generate energy carriers) [18,19].

3. Illustrating the approach with data from the oil and gas sector of Brazil

3.1. Framing of the analysis

Despite Brazil's production of biofuel (notably ethanol from sugarcane) and ample hydroelectric generation, in 2010 fossil energy accounted for more than 50% of the total primary energy sources consumed by Brazil [49]. In 2010, domestic production of oil (biophysical) was equivalent to 109.6 MTOE or approximately 4600 PJ/year (Gross Energy Equivalent Thermal) [49] and that of natural gas was 12.5 MTOE or approximately 525 PJ/year [31]. About 85% of this supply of thermal energy in the form of oil and gas was from off-shore areas, most of which concern deep and ultra-deep water [14].

Adopting the external view, we consider here two domestic primary energy sources in terms of their biophysical supply: (i) tonnes of oil; and (ii) m^3 of natural gas. Both can be converted to joules belonging to the category ‘PES-thermal’.

Adopting the internal view, we characterize the network of energy transformations taking place in four functional compartments of the oil and gas sector as follows: (i) exploration and extraction of primary energy sources (although in the jargon of engineers the extraction of oil is often called ‘production’, recall that PES cannot

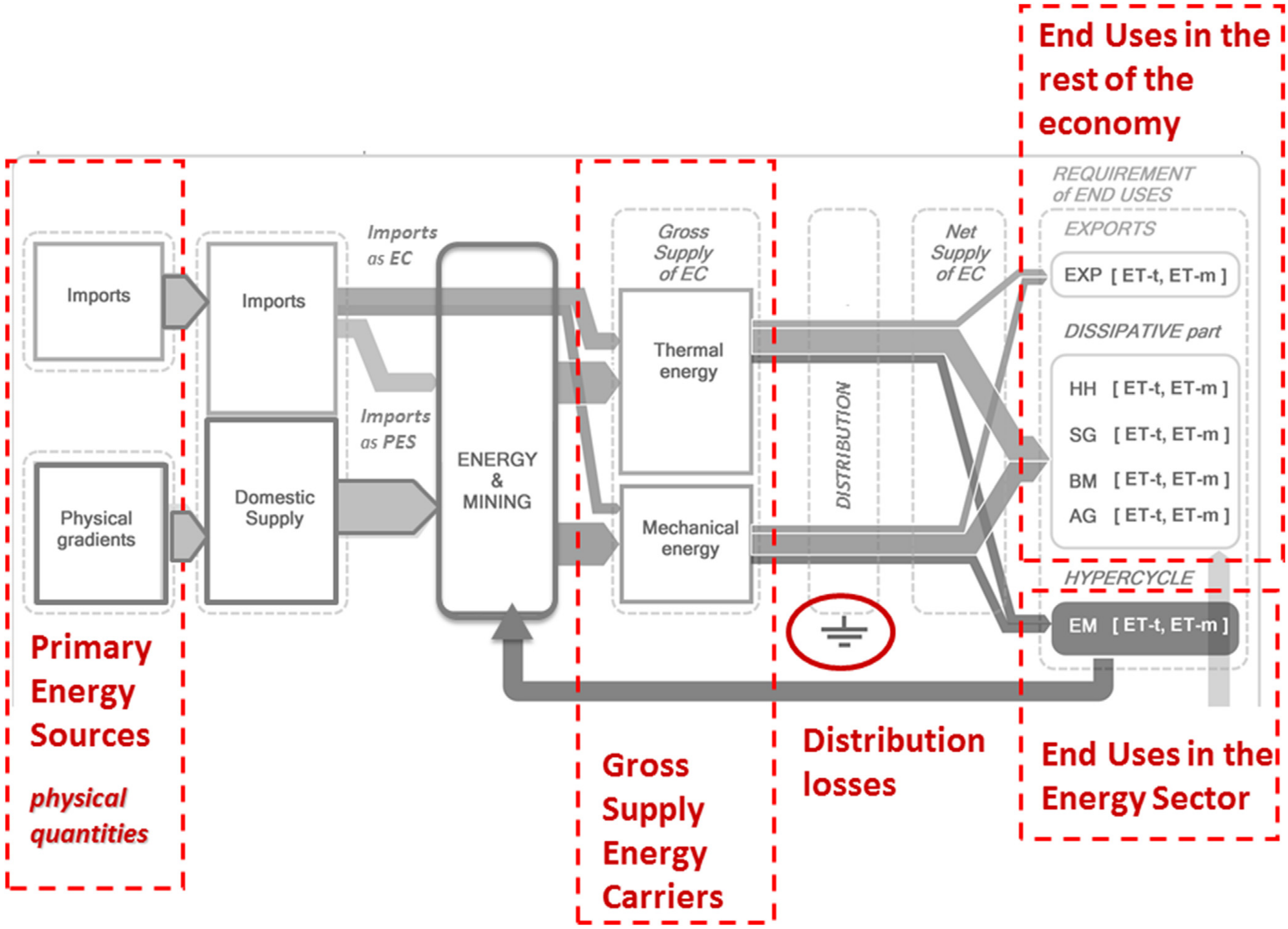

Fig. 3. Example of an energy grammar based on MuSIASEM (adapted from Ref. [15]. (Abbreviations: EC = energy carrier; EXP = export; HH = household sector; SG = service and government sector; BM = building and manufacturing sector; AG = agricultural sector, EM = energy & mining sector; ET-t = energy throughput thermal; ET-m = energy throughput mechanical).

be 'produced'!); (ii) transport of PES; (iii) refining and processing of PES (oil and gas) into energy carriers (fuels); and (iv) delivery of energy carriers (fuels) to the various sectors of the economy. Different types of technical inputs are required to operate these four functional compartments: (i) inputs of energy carriers: gasoline, diesel, bunker fuels (thermal) and electricity (mechanical); (ii) inputs of labor hours.

The output of the oil and gas sector is a mix of energy products, such as gasoline, diesel, fuel oil, jet fuel. The major share of this output is used for transportation, followed by industrial production and residential uses.

Following this conceptualization, we arrive at the representation of the taxonomy of categories of energy flows shown in Table 1. Note that the classification of energy uses in national statistics does not always perfectly match the categorization of end-uses in MuSIASEM. For instance, in the MuSIASEM accounting the energy carriers consumed in transportation is partly included in the household sector (referring to the consumption of private vehicles) and partly in the service and government sector (referring to the consumption of transport companies or public transportation).

The huge territorial dimension of Brazil implies significant energy costs for transportation. Indeed, it is important to recognize that the exploration and extraction of oil and gas is concentrated in

Table 1
Accounting categories in the external and internal view.

External view	Internal view	
Primary energy sources (PES)	Energy carriers (EC)	End-uses
Oil and gas	Gasoline	Household
	Diesel	Service & government
	Coke	Building & manufacturing
	Heating oil	Agriculture & fishing
	Jet fuel	Energy & mining
	Electricity	Export
	Others	

offshore areas and that distances to refineries and final end-uses are large [30,46]. According to [1]; the exploratory activity of oil and gas in Brazil covers an area of 315 thousand km^2, with almost 429 oil or natural gas fields. Approximately 85% of the extraction takes place at sea, especially in deep and ultra-deep waters. An overview of the infrastructure of the Brazilian oil and gas sector is given in Fig. 4.

3.2. First quantitative assessment of the different functional compartments

3.2.1. Exploration and extraction

For the activity of 'exploration and extraction of oil and natural gas' we organized the data in relation to onshore and offshore processes, and the offshore activities were further divided into five types of platforms: fixed, FPSO (floating production, storage and offloading), explorer ship, and semi-submersible. This distinction is necessary because the extraction process on land and at sea implies a completely different use of production factors (labor, electricity and fuels). The inputs of energy carriers for the activities of exploration and extraction are represented by oil products, natural gas and electricity. The consumption of fuel is basically diesel for self-production of electricity but oil is often also used. In the accounting for the input of electricity we therefore have to make a distinction between quantities that are: (i) locally self-produced using diesel, oil and natural gas; or (ii) purchased directly from the grid [6,20,22,29,38,42,45]. Table 2 shows the use of energy carries, expressed in PJ, in exploration and extraction in Brazil in 2010.

3.2.2. Transport 1 – from oil and natural gas fields to conversion plants

For the activity of transport of oil and gas from the fields to the processing centers (oil refineries and natural gas plants) we organized the data in relation to the flows of energy carriers needed to operate three technological processes: (i) pipelines; (ii) ships and barges for coast cabotage and ships for long-distance/oversea; (iii) trucks. As extraction is concentrated at sea, most of the transportation is by ships and barges, covering a coastline of 7,500 km. The mix of inputs of energy carriers includes: (i) marine fuels for boats/barges (diesel); (ii) marine fuel bunker (mix of diesel and residual fuels) for ship; and (iii) natural gas for pipelines

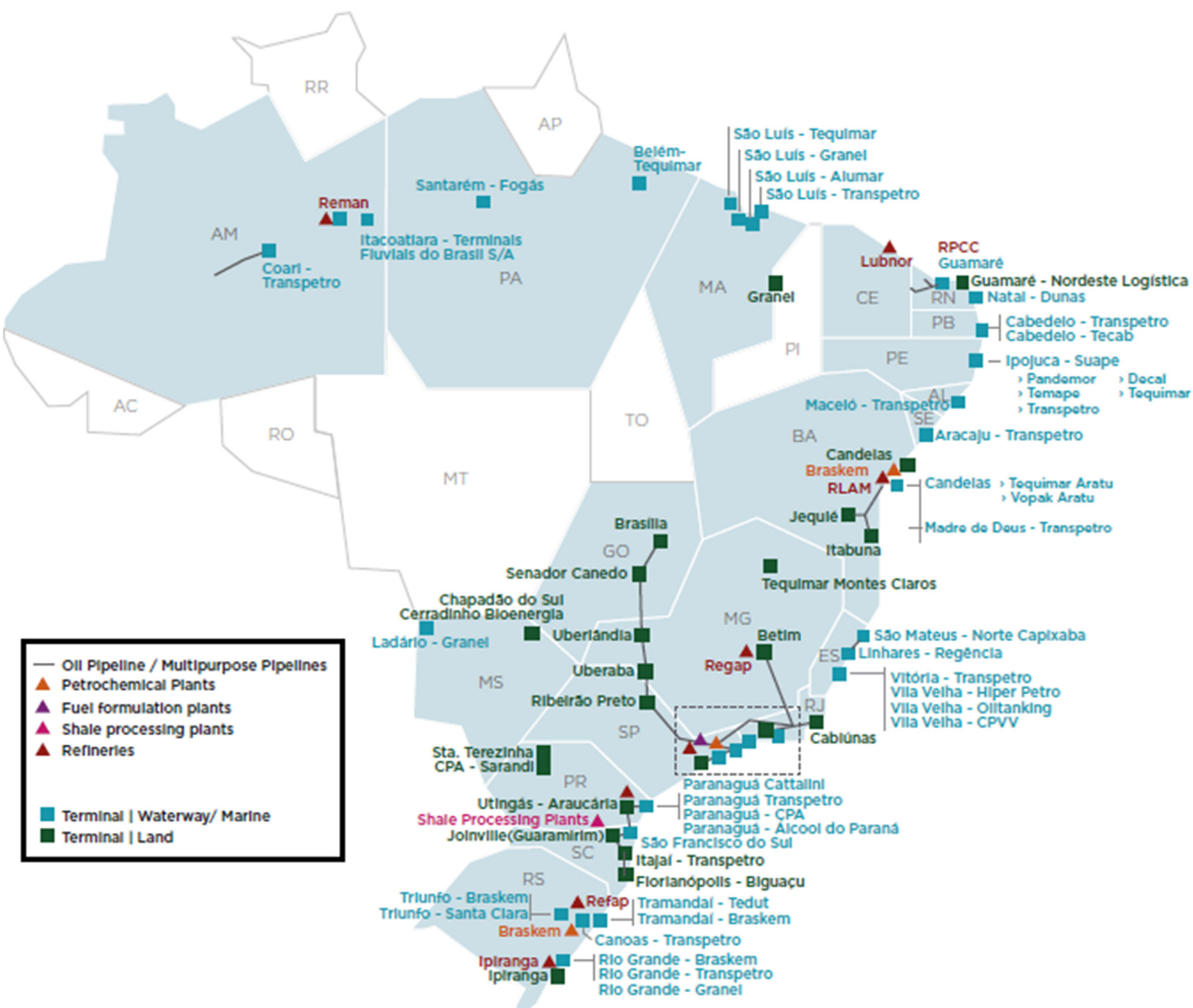

Fig. 4. Oil and gas infrastructure in Brazil. Data from Ref. [1].

Table 2
Use of energy carriers (in PJ) for exploration and extraction in Brazil, 2010.

Activity	Requirement of production factors energy carriers (PJ)				
Exploration & production	Oil products		Natural gas		Electricity from grid
	Thermal	Electricity[a]	Thermal	Electricity[a]	
Onshore	*6.2*	*1.7*	*23.5*	*6.4*	*0.9*
Fixed	6.2	1.7	23.5	6.4	0.9
Offshore	*31.8*	*8.6*	*123.9*	*33.5*	*4.5*
Fixed platform	17.9	4.8	69.7	18.8	2.5
FPSO	8.5	2.3	33.2	9.0	1.2
Explorer ship	0.8	0.2	3.2	0.9	0.1
Semi submersible	4.6	1.2	17.8	4.8	0.6
TOTAL	*38.0*	*10.3*	*147.5*	*39.8*	*5.4*

Data from Refs. [1,14].
[a] Local 'self-production' from oil or natural gas (not from grid).

[22,32,33,41]. Table 3 shows the use of energy carries, in PJ, by transport activity in Brazil for 2010.

3.2.3. Conversion plants (oil and gas refineries)

As regards the activity of transforming the primary energy sources oil and gas into fuels (the mix of oil products) we organized the data according to three typologies of processes related to plant size. For oil refineries: (i) small, i.e., processing less than 20×10^3 m^3/day; (ii) medium, i.e., processing between 20–50 $\times 10^3$ m^3/day; and (iii) large, i.e., processing more than 50×10^3 m^3/day. For natural gas plants: (i) small, i.e., processing less than 5×10^6 m^3/day; (iii) medium, i.e., processing between 5–10 $\times 10^6$ m^3/day; and (iii) large, i.e., processing more than 10×10^6 m^3/day. The mix of inputs of energy carriers to support this activity includes: (i) oil products (fuels); (ii) natural gas; and (iii) electricity. The oil products are basically distillate or residual fuel oils. As for electricity, also in this case we distinguish between the electricity that comes from self-generation (using oil products or natural gas) and that purchased directly from the grid [4,21]. Table 4 shows the use of energy carries, in PJ, for conversion plants in Brazil in 2010.

3.2.4. Transport 2 – to end users

For the activity of distribution of the oil and gas products (the different fuels used by society) from the conversion plants to the end-users (transport sector, industry, residential, services) we consider three processes: (i) pipelines, (ii) ship/barges and (iii) trucks. Table 5 shows the use of energy carries for these activities, in PJ, in Brazil in 2010. The mix of inputs of energy carriers for this activity includes: (i) marine fuels (bunker) for ship; (ii) natural gas for pipelines; and (iii) diesel fuel for trucks [2,5,22,23,36,37]. Note that most of the consumption of energy carrier (90%) for distribution is accounted for by trucks.

3.3. Bridging hierarchical levels and top-down and bottom-up information

The results presented in Tables 2–5 are integrated in the overview given in Table 6. In this table we include also a rough estimate of the labor input (in hours per year) in the different functional sectors, using data from Refs. [39] and [43]. Note that this paper focuses on illustrating the MuSIASEM methodology and does not pretend to provide an accurate assessment of the labor requirement in the Brazilian oil and gas sector. The numbers given here have the sole purpose of illustrating the approach. By adopting more complex grammars one can include other relevant inputs required for the operation of both structural and functional types in the energy sector (e.g., power capacity, water) not considered in this study. Again, note that the electricity (mechanical energy) that is locally generated from fuel (not from grid) is not included in the accounting of inputs of mechanical energy for the energy sector to avoid double counting: this input to the energy sector is already included in the input of fuels (thermal energy) consumed for the self-production of electricity in the plant. However, a more elaborated grammar can be designed for in depth studies to include information on the relative importance of self-generation of electricity with regard to the requirement of power capacity (technology used in the plant for this task).

Data organization represents an important feature of MuSIASEM. In fact, by organizing the data as shown in Table 6, we see for each functional compartment of the oil and gas sector and for each of the technologies employed in these compartments the requirement of production factors, that is, the inputs of different types of energy carriers (thermal and electric) as well as the input of labor. In this way we are describing the same system simultaneously at different hierarchical levels of organization: the level of the oil and gas sector as a whole (level n), the level of the functional

Table 3
Use of energy carriers (in PJ) for transport from oil and gas fields to the conversion plants.

Activity	Requirement of production factors energy carriers (PJ)					
Transport to conversion plants	Diesel fuel		Residual fuel		Natural gas	
	Thermal	Electricity[a]	Thermal	Electricity[a]	Thermal	Electricity[a]
Pipelines (oil & gas)	–	–	–	–	1.8	0.6
Ship/Barges	2.3	–	6.9	–	–	–
Cabotage (coastal)	*0.6*	–	*1.8*	–	–	–
Oversea	*1.7*	–	*5.1*	–	–	–
Trucks	18.0	-	-	-	-	-
Total	*20.3*	-	*6.9*	-	*1.8*	*0.6*

Data from Refs. [1,13,14].
[a] Local 'self-production' from oil or natural gas (not from grid).

Table 4
Use of energy carriers (PJ) for oil and gas conversion plants in Brazil, 2010.

Activity	Requirement of production factors energy carriers (PJ)				
Transformation	Oil products		Natural gas		Electricity from grid
	Thermal	Electricity[a]	Thermal	Electricity[a]	
Oil Refineries	*181*	*5.6*	*53.7*	*1.7*	*7.0*
Small (<20 × 10^3 m^3/day)	90.4	2.8	26.8	0.8	3.5
Medium (20–50 × 10^3 m^3/day)	79.1	2.4	23.5	0.7	3.1
Large (>50 × 10^3 m^3/day)	11.3	0.3	3.4	0.1	0.4
Natural gas plants	*0*	*0*	*53.4*	*14.4*	*1.5*
Small (<5 × 10^6 m^3/day)	0	0	34.3	9.3	1.0
Medium (5–10 × 10^6 m^3/day)	0	0	11.4	3.1	0.3
Large (>10 × 10^6 m^3/day)	0	0	7.6	2.1	0.2
Total	*181*	*5.6*	*107.1*	*16.1*	*8.5*

Data from Refs. [1,8,14,51].
[a] Local 'self-production' from oil or natural gas (not from grid).

Table 5
Use of energy carriers (PJ) for distribution of energy carriers to end users in Brazil, 2010.

Activity	Requirement of production factors energy carriers (PJ)					
Transport for distribution to end-users	Diesel fuel		Residual fuel		Natural gas	
	Thermal	Electricity[a]	Thermal	Electricity[a]	Thermal	Electricity[a]
Pipelines (oil and gas products)	–	–	–	–	1.3	0.4
Ship/Barges	2.3	–	6.3	–	–	–
Cabotage (coastal)	0.6	–	1.6	–	–	–
Oversea	1.7	–	4.7	–	–	–
Trucks	88.8					
Total	*91.0*	-	*6.3*	-	*1.3*	*0.4*

Data from: Refs. [1,13,14].
[a] Local 'self-production' from oil or natural gas (not from grid).

Table 6
Requirement of the production factors energy and labor in the Brazilian oil and gas sector (level n), reported over two hierarchical levels –functional compartments (level n−1) and technological processes (level n−2)– in relation to the total throughput of 118 Mm^3 of Oil Equivalent/year (103 MBarrels of Oil Equivalent/year or 4350 PJ). Data refer to the year 2010.

Functional compartment	Process	PES throughput (10^6 m^3 of oil equiv/yr)	Mix (%)	Production factors (inputs) consumed		
				Labor (10^6 h)	Fuel (TJ)	Electricity (TJ)
Exploration & production	Onshore	12	10%	38	29.7	1.0
	Offshore	106	90%	200	156	4.5
	Sub-total	*118*	*100%*	*238*	*186*	*5.5*
Transport to refinery	Pipelines	60	50%	1	1.8	0
	Ships	29	25%	20	9.1	0
	Trucks	29	25%	60	18.0	0
	Sub-total	*118*	*100%*	*81*	*29*	*0*
Refinery	Small	18	15%	28	152	4.5
	Medium	75	64%	25	114	3.5
	Large	25	21%	3.5	22.3	1.0
	Sub-total	*118*	*100%*	*57*	*288*	*9.0*
Transport to end-users	Pipelines	29	25%	3	1.3	0
	Ships	15	12%	22	8.6	0
	Trucks	74	63%	225	89	0
	Sub-total	*118*	*100%*	*250*	*99*	*0*
Total oil & gas sector		*118*		*626*	*602*	*14.5*

compartments (level n−1), and the level of individual technological processes within the compartments (level n−2). The sub-totals for the various functional compartments (level n−1) shown in Table 6 refer to *extensive* variables: they concern top-down assessments derived from national statistics and describe the overall input (end-uses of production factors) and output flows for the various functional compartments (for a specific year). These data cannot be related directly to the technical coefficients (bottom-up information) of the various individual processes taking place at the local scale (level n−2). In order to scale information across different hierarchical levels, we need data on the relative size (weight) of the different technological processes taking place within each functional compartment (at the local scale, n−2). This information is given in Table 6 in the column 'Mix (%)'; it shows what percentage of the overall throughput is processed by what technology and therefore indicates the relative role (importance) that individual technologies play in determining the performance of the oil and gas sector as a whole.

In Fig. 5 we represent the same information in a different way to emphasize the role of data arrays and matrices making it possible to integrate bottom-up and top-down information in MuSIASEM. Horizontal data arrays on the right side of Fig. 5 represent a

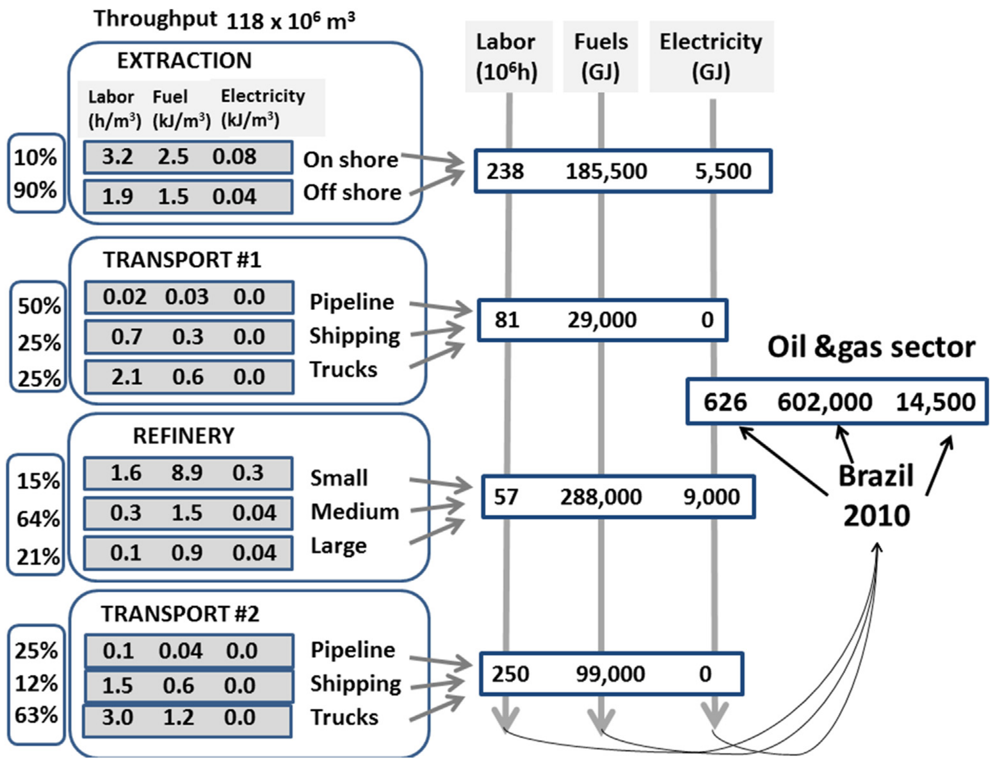

Fig. 5. MuSIASEM accounting scheme including unitary end-uses vectors for local processes (left, indicated in grey), the relative weight of processes (extreme left), and aggregate data referring to the characteristics of functional compartments and sectors (right).

quantitative characterization of end-uses for the functional compartments. They describe the production factors (in quantity and quality) required to express the function of the relative compartment. For example, for 'refinery' we have an end-use data array of [57, 288, 9] in which the three elements indicate the yearly input of, respectively, labor (in 10^6 h), thermal energy carrier (in PJ), and electricity (in PJ). These end-uses are derived from statistics (top-down information) and refer to a specific situation, that is, the Brazilian oil and gas sector in 2010.

Horizontal data arrays on the left side of Fig. 5 (in grey) represent unitary end-use data arrays characterizing the various technological processes (structural types) employed in the functional compartments. They represent the inputs of production factors typically required per unit of throughput processed by the technology in question. These technical coefficients are defined at the local scale (bottom-up information). For example, on-shore exploration and extraction in Brazil typically requires 3.2 labor hours, 2.5 GJ of fuel, and 0.08 GJ of electricity per 1 m^3 of oil equivalent processed. The unitary end-use data array is made of *intensive* variables and therefore can be scaled-up by multiplying by the size of the process throughput (e.g., 12×10^6 m^3 of oil equivalent processed in on-shore exploration and extraction in 2010).

Unitary end-use data arrays characterize the performance of a given technological process in terms of a specific *profile* of inputs (labor, fuels and electricity) and hence provide a much richer and better description of the process than the conventional single input/output ratios used to define efficiency. In fact, when dealing with the networks of energy transformations of modern energy systems, both inputs and outputs of technological processes invariably concern *specific combinations (mixes) of input and output flows*. Analysis of single individual flows necessarily gives an incomplete and often misleading picture of the situation. The use of data arrays provides a flexible solution to this problem. Depending on the scope of the study, one can select the relevant inputs for inclusion in the end-use data array.

The vertical data arrays on the very left side of Fig. 5 describe the relative importance (weight) of the different processes taking place in each functional compartment as a fraction (or percentage) of the total throughput. For example in refinery we have [15, 64, 21] the relative percentages of the load of the throughput processed by the different structural types (types of refinery) used in the functional unit. This information, together with the total throughput of the oil and gas sector (118 $\times$ 10^6 m^3 of oil equivalent processed) is necessary to scale up the information given by the unitary end-use vectors (level n−2) to obtain the total aggregate input (end-use) of production factors at the functional compartment level (n−1). Thus, the multi-scale accounting illustrated in Fig. 5 establishes a bridge between assessments performed at different hierarchical levels of organization and can be used to (i) scale up information referring to unitary operations, and (ii) to interface or confront 'top-down' (statistical data referring to the characteristics of functional compartments at level n−1) with bottom-up information (technical coefficients of local technological processes at level n−2). This scaling is particularly useful for the discussion of the feasibility and viability of scenarios in which one can imagine different combination of technologies.

In conclusion, the use of unitary end-use data arrays complemented by the relative weight of processes is extremely important for a comprehensive understanding of the functioning of the entire oil and gas sector and in the design of scenarios for energy policies. Indeed, the accounting scheme illustrated in Fig. 5 allows us to retrieve the same information as given in Tables 2–6 but at the same provides us with a much richer understanding of the role that the different technological solutions play in the overall domestic supply of oil and gas. In fact, in this way we can:

(i) Calculate from the unitary end-uses matrices (the set of data arrays determined by the different technical processes in each functional compartment) the aggregate consumption of inputs in each one of the four functional compartments of the Brazilian oil and gas sector (scaling up), considering not only the various types of energy carrier consumed, but also other relevant production factors, such as labor (but we can add to this accounting assessments of water, power capacity, other key material).

(ii) Facilitate comparative studies across countries by comparing the characteristics (consumption of the mix of inputs) of both the whole oil and gas sector and its individual functional compartments and processes. This allows us to quickly individuate the factors that determine significant differences in the performance of the energy sector and its technologies among different countries. Indeed, the same functional compartment can have a completely different profile of unitary end-use vectors depending on the technologies employed. In this case we are relying on bottom-up information and the relative importance (weight) of the various processes used in the functional compartment. The specific combination of technological processes —structural types— used in a functional compartment will affect its overall characteristics.

4. Conclusion

The preliminary results obtained when trying to implement a multi-level integrated accounting of the oil and gas sector of Brazil show that it is possible to formally bridge the performance of the whole oil and gas sector to the performance of its functional and structural components. More specifically this application of MuSIASEM shows that this approach allows us to:

(i) Study the factors that determine the overall performance of the oil and gas sector looking at different indicators. For example, when looking at the big picture we find that the oil and gas sector produces a supply of 4350 PJ/year and consumes 600 PJ/year in terms of fuels (measured in thermal energy). In relation to the flows of fuels the oil and gas sector has an output/input slightly larger than 7/1. However, we have to add to this thermal input an additional requirement of energy input of 14.5 PJ of electricity (that could represent another 38 PJ/year if these PJ were produced using fossil energy). This fact illustrates the need of considering the performance of individual sub-sectors at the level of the whole energy sector where the effects of the internal loop of consumption of energy carriers to produce energy carriers can be accounted for. Very important is also the requirement of labor per unit of energy delivered in the form of energy carrier (in this case fuels). For example, our data show that in 2010 the Brazilian oil and gas sector generated a supply of 7 GJ of liquid fuels per hour of labor. A similar analysis of the Brazilian biofuel sector, using data of the year 2003, shows a production of ethanol of about 0.5 GJ of liquid fuel per hour of labor [16]. As observed earlier, our assessments of the labor requirement are rough estimates. All the same, these preliminary data flag an enormous difference in labor productivity: the production of ethanol requires 14 times more hour of labor per net supply of thermal output than the production of fuels from fossil energy. This difference points at a lower economic convenience for the socio-economic process of ethanol production from sugarcane compared to the production of gasoline and diesel from oil.

(ii) Study the factors that determine the overall performance of the oil and gas sectors across different hierarchical levels of analysis. The accounting done with MuSIASEM is able to deconstruct the overall output/input ratio of the whole oil and gas sector scaling down to the analysis to the profile of inputs and outputs of each one of the four functional compartments by considering the relative size of operations. Then, within each one of these functional compartments it is possible to study, in cascade, the profile of inputs and outputs of each of the technical solutions used within the compartments for expressing their specific tasks. In this way it is possible to generate a more robust assessment of the whole sector across levels of organizations and scales by combining top-down information (coming from statistical data) and bottom-up information (coming from technical analysis of unitary operations). For example, the energy spent at the level of individual extraction plant may be not fully accounted for, when small topping plants are used to self-produce the fuels used in the extraction. In this case, an analysis of the energy flows taking place at the local scale, in the process of extraction (bottom-up inference) can be used to check whether the official energy statistics are under-estimating the energy consumption taking place in this functional compartment. This may be a common case in oil extraction (Rony Parra Jácome, personal communication);

(iii) Facilitate comparative studies of the performance of specific energy sub-sectors of Brazil with analogous sub-sectors operating in other countries. In fact, the use of an integrated and multi-scale analysis to compare energy sectors of different countries makes it possible to individuate the factors that determining differences for the whole sector across the different hierarchical levels of organization of the sector, as well as the factor determining different for individual functional compartments. For example, applying the accounting scheme illustrated in Fig. 5 to the oil and gas sectors of two different countries, we can answer the following questions: Are the mix of technologies used to express the same tasks similar? How different are the technical coefficients of analogous processes when assessed in terms of unitary operations? What is the relative importance of the different processes used for expressing analogous tasks?

(iv) Design scenarios of the effects of possible changes in the technological coefficients of specific processes or changes in the mix of technological solutions adopted in the different compartments or changes in the relative importance (weight) of the processes employed. The MuSIASEM system of accounting facilitates the scaling up or down of the implications of proposed changes and combinations of changes in different scenarios exploring the option space. If a detailed analysis of the type illustrated in this paper for the oil and gas sector would be available also for the other sub-sectors of the energy sector, especially considering the processes dealing with the production of electricity, it would be possible to gain a better understanding of how the characteristics of individual processes and relative technical coefficients do affect the performance of the energy sector as a whole.

The present work is a preliminary study and the next step of our analysis requires a refinement of the taxonomy of structural types, including a more detailed definition of the various plants and technologies presently operating in the different functional compartments of the oil and gas sector of Brazil and their technical coefficients. In fact, it should be noted that the structural types defined in Fig. 2 – e.g. small refinery and large refineries – are categories that still can imply a large level of variability (especially if considering different typologies of crude oil). This point will require further analysis to assess how robust is the choice of categories used in the multi-scale analysis. Our next step will be the integration of actual data describing the operation of actual plants within the different functional compartments in terms of technical coefficients in the system of accounting described so far. In this way it will become possible to address also the effect of other factors (such as the utilization factor and the power load of the structural types) that affect the overall conversions ratios.

In spite of these shortcomings, we believe that the material presented in this paper illustrates that the logic of the MuSIASEM accounting framework helps in:

(i) improving the understanding of the relations over the characteristics of the different elements making up the metabolic pattern of the energy sector. It makes it possible to map across scales the requirements of different types of inputs needed for obtaining different types of outputs;
(ii) generating a more robust quantitative characterization of energy systems (defined at different levels and scales) by combining together information obtained by adopting a bottom-up analysis (technical analysis at the plant level) and top-down analysis (aggregate assessment from statistics);
(iii) characterizing the performance of the whole energy sector by repeating the same analysis done here for the oil and gas sector to other sectors exploiting different primary energy sources (hydroelectric sector, biofuels sector, photovoltaic sector, etc) and scaling up the different characterizations of performance.

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