Energy Policy 122 (2018) 63–74

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The metabolism of oil extraction: A bottom-up approach applied to the case of Ecuador

Rony Parra[a,b,*], Louisa Jane Di Felice[b], Mario Giampietro[b,c], Jesus Ramos-Martin[a]

[a] Grupo de Población y Ambiente, Universidad Regional Amazónica Ikiam, Vía Muyuna-Atacapi, Km.7, Tena 150102, Ecuador
[b] Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[c] ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain

ARTICLE INFO

JEL codes:
Q02
Q35
Q41
Q57

Keywords:
Oil extraction
MuSIASEM
Ecuador
Metabolism
Complexity

ABSTRACT

The global energy system is highly dependent on fossil fuels, which covered approximately 90% of primary energy sources in 2016. As the quality and quantity of oil extracted changes, in response to changes in end uses and in response to biophysical limitations, it is important to understand the metabolism of oil extraction – i.e. the relation between the inputs used and the output extracted. We formalize a methodology to describe oil extraction based on the distinction between functional and structural elements, using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to generate a diagnostic of the performance of oil extraction and to build scenarios. The analysis allows generating modular benchmarks which are applicable to other countries. It is shown that oil extraction in Ecuador consumes, per cubic meter of crude oil extracted, over 100 kWh of electricity and 1.5 GJ of fuels, requiring 3 kW of power capacity and 2 h of human activity. A scenario is developed to check the effects on Ecuador's metabolic pattern of an increase in oil production over the next five years. The strength of the proposed methodology is highlighted, focusing on the adaptability of the method for dealing with policy issues.

1. Introduction

Despite efforts to reduce greenhouse gas (GHG) emissions and to shift towards a renewable energy system, oil remains an essential part of the global energy chain, with 3820 Mtoe consumed in 2015, out of a total final energy consumption of 9383 Mtoe (International Energy Agency, 2017). This is partly due to the fact that most renewable systems propose an alternative to electricity, rather than fuels. With sustainability issues tied to biofuels, particularly due to concerns over land use in relation to food security (Rathmann et al., 2010), as well as their low energetic output (Rajagopal et al., 2007), it is unlikely that conventional fuels will be phased out in the near future. Given the huge role that oil plays in societies, it is important to understand its metabolism – intended here as the interaction of internal factors determining the relation between the profile of inputs and outputs - particularly in relation to the internal consumption of energy carriers and other flows and funds (see Section 3.1 for a definition), such as water, chemicals, power capacity and human activity.

Most existing studies on the metabolism of the oil extraction sector account for one input of interest, as shown in Section 2. However, holistic assessments taking into consideration more than one fund or flow at a time, and at different levels, are lacking. Through the use of a Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), one of the aims of this paper is to fill this methodological gap. We propose an alternative approach to formalize the grammar associated with the oil extraction process in Ecuador, following previous studies found in the literature for the oil and gas sector in Brazil (Aragão and Giampietro, 2016), the gas sector in Mexico (González-López and Giampietro, 2018) and for the electricity metabolism of Catalonia (Di Felice et al., this issue).

The aim of the paper is two-fold: on one hand, to develop methodological tools allowing us to describe the oil extraction process by accounting for various flows and funds across different levels; on the other, to apply the methodology to the case of Ecuador, both characterizing the factors determining the current metabolism and developing a scenario for future extraction and policy.

Section 2 provides background information as well as a review of existing literature. Section 3 outlines the rationale behind MuSIASEM and its proposed energy grammar, focusing on the distinction between functional and structural elements as applied to the oil extraction

---

* Corresponding author.

E-mail addresses: rony.parra@ikiam.edu.ec (R. Parra), louisajane.difelice@uab.cat (L.J. Di Felice), mario.giampietro@uab.cat (M. Giampietro), jesus.ramos@ikiam.edu.ec (J. Ramos-Martin).

https://doi.org/10.1016/j.enpol.2018.07.017
Received 18 January 2018; Received in revised form 2 June 2018; Accepted 10 July 2018

process; then, data sources and their reliability are discussed. Results and discussion are provided in Section 4, showing how the oil extraction grammar is built through a bottom-up approach. Finally, the paper illustrates a scenario of future oil extraction in Ecuador, showing how the modular bottom-up grammar can be applied to check constraints on future states. We end by summarizing the main findings, both with respect to the methodology and its possible broader applications in energy policy, and by highlighting areas for improvement and future research.

2. Background and literature review

Latin America is a net exporter of oil and gas, and public policies are pushing for an increase of extraction and refining capacity over the coming years, although regulations vary across countries (Hollanda et al., 2016). In Ecuador, as conventional oil stocks become depleted over time, government projections of reserves suggest that a shift from light and medium to heavy oil is gradually taking place (Secretaria de Hidrocarburos, 2016a). Oil extraction in Ecuador is minor (28 Mtoe in 2015) compared to other Latin American countries such as Mexico (131 Mtoe in 2015) or Brazil (133 Mtoe in 2015) (International Energy Agency, 2017). Nevertheless, extraction in Ecuador at the national level has been growing consistently over the past years, almost doubling between 2000 and 2014 (Hollanda et al., 2016). The amount of oil extracted is beyond the country's refining capacity, meaning that the country is a net exporter of crude oil, and net importer of fuel products. The two main energy policies in Ecuador over the past years have been, on one hand, the construction of new hydropower dams (MICSE, 2016) and, on the other, the development of refinement capacity, with the construction of a refinery *(Refinería del Pacífico* – Pacific Refinery) which will allow the processing of an additional 300,000 barrels of oil per day (MICSE, 2016), bridging the gap between oil extracted and fuels refined.

On the extraction side, since the reform on the hydrocarbon law of July 2010 (Asamblea Nacional, 2010), there has been a shift from participation contracts to service provision contracts. In 2012 a policy was established to "commercialize oil and its exported secondary products, preferably with state companies and public consumers" (author's translation, from (EP Petroecuador, 2012)). This allowed strengthening Ecuador's role in international markets, as it now has sale agreements on future oil lasting up to 2024. As a consequence, the country's economy would be strongly affected by a decrease in extraction over the coming years, especially if we take into account that, in 2015, oil exports accounted for 6662 Million dollars, or 36% of total exports (Ministerio de Comercio Exterior, 2016).

Overall, Ecuador's policy goals outlined in the national energy agenda of 2016–2040 point towards an extension of the hydrocarbon horizon, with a focus on crude oil and natural gas, in order to meet local consumption and increase exports. Within this context, it is important to understand how the current metabolism of oil extraction works, and to assess the effects of such policies on the country's future energy metabolism.

Zooming out of the case study at hand and looking at wider discourses of oil extraction, while the popularity and perceived urgency of the concept of peak oil varies across research groups, it is clear that there is a global shift towards the extraction of unconventional oil and oil shale, requiring higher technological and energetic investments (World Energy Council, 2016). Various assessments have been carried out focusing on the amount of energy needed to extract oil, mostly using energy return on energy investment (EROI) or life cycle assessments (LCA).

LCAs provide detailed overviews of the inputs and outputs of processes, but their role as input for policymaking has been questioned by various authors ((Ayres, 1995), chapter 4 of (Horne et al., 2009)). This is mostly due to three limitations: firstly, information is often reduced to a single parameter or indicator, which precludes the transparency of the calculation, providing a single output parameter rather than an overview of the process; secondly, choosing "the right" boundaries is problematic, leading to vastly different results being produced for the same process; thirdly, and most importantly for the current study, LCAs don't allow appropriate scaling across different levels of analysis. We will clarify what we mean by this through the steps of the proposed methodology.

Current assessments of oil extraction processes have mostly focused on either assessing oil reserves within a peak oil context (Owen et al., 2010), checking the environmental impacts of oil extraction (Bravo, 2007), or quantifying the energy returned on energy invested (EROI) (Court and Fizaine, 2017; Murphy and Hall, 2011). Extensions of EROI which use eMergy also exist (Chen et al., 2017), as well as other studies which analyze the EROI of particular technologies, such as biodiesel production (Poddar et al., 2017).

Most of the recent analyses on energy consumption in fossil fuel extraction focus on oil sands (Brandt et al., 2013b; Lazzaroni et al., 2016; Nimana et al., 2015). Brandt et al. (2013b), for instance, compute the energy return ratios for the period between 1970 and 2010, proposing an LCA-oriented methodology to calculate the energy return. An important difference between their methodology and the one presented here is that Brand et al.'s work does not split inputs into different energy carriers. We will argue that this distinction is of paramount importance to understand the behavior of energy systems. Other studies analyze particular cases of technologies, such as microalgae oil extraction (Peralta-Ruiz et al., 2013), including the energy consumption of the process by using exergy analysis.

In a different piece of work, Brandt et al. (2013a) present a bottom-up LCA-based and matrix-based approach for calculating systems-scale energy efficiency and net energy returns. To our knowledge, this is the closest exercise to the one presented here, as it allows working with different scales. Given the lack of distinction between funds and flows in Brand et al.'s work, the method presented here can be viewed as complementary to their approach, integrating it with additional information that can be of particular relevance to policy. Top-down, input-output methods have also been used to estimate the energy use of fossil fuels extraction, as in the case of shale gas extraction in China (Chang et al., 2014). Here, despite having information on the different inputs used in the process of shale gas extraction (energy carriers, water, sand, gravel, etc.), all inputs are converted into energy requirements. We argue that it is important to maintain a level of disaggregation in the description of inputs and outputs of the energy system.

Less attention is given in the literature to the use of water for the extraction of primary sources and their conversion to liquid fuels. Ali and Kumar (2017) provide an exception, by focusing on the water demand coefficients over the life cycle of fuels produced from crude oil. Their coefficients, although calculated for US wells, are of similar magnitude to the ones presented here.

Focusing back to the case of Ecuador, studies highlighting different dimensions of oil extraction have been carried out. FLACSO has produced a series of studies reviewing the current state of oil extraction in relation to sustainable development (Fontaine, 2003). From an environmental justice perspective, a number of studies have assessed the social and environmental impacts of oil extraction on local populations (see, for example, (Vallejo et al., 2015) and (Rodríguez, 1998)). The environmental impacts of oil extraction on aquifers and water consumption have not been assessed specifically for Ecuador, but studies on the topic exist, for example in relation to deep sea drilling (Cordes et al., 2016) and shale gas extraction (Vidic et al., 2013).

In order to contribute to the debate on the metabolism of oil extraction, this study presents the application of a new methodology of accounting for the different funds and flows employed, as described in the next section.

3. Materials and methods

3.1. MuSIASEM and the energy grammar

Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is an accounting scheme developed by Giampietro and Mayumi (Giampietro, 2003; Giampietro et al., 2013, 2011, 2009; Giampietro and Mayumi, 2000; Pastore et al., 2000). The approach provides an application of Georgescu-Roegen's flow-fund scheme (Georgescu-Roegen, 1971), linking socioeconomic and biophysical variables in an integrated way.

The use of grammars is key to the approach. A grammar can be seen as a set of relations linking formal categories to semantic categories. In brief, this means that data, in this case referring to energy, is organized in a way that makes sense of the relations expected in a functional whole, linking elements operating at different levels of the system, and maintaining crucial distinctions between components that play different functions.

The MuSIASEM energy grammar has been described and applied in detail – see, for example, Velasco-Fernandez et al. (2015) and Giampietro et al. (2014). Its two main concepts, essential to understand the proposed analysis, are the distinction between primary energy sources (PES) and energy carriers (EC), and the disaggregation between mechanical energy (electricity) and thermal energy (heat and fuels). Fig. 1 shows the formalization of MuSIASEM's energy grammar. A list of the acronyms introduced in Fig. 1, and used throughout the paper, is also provided in Table 1.

Another pillar of MuSIASEM is the distinction between funds and flows, following Georgescu-Roegen's fund-flow model (Georgescu-Roegen, 1970). A detailed description on the importance of defining funds, flows and fund/flow ratios for MuSIASEM can be found in Giampietro et al. (2014). To summarize, funds are elements whose identity remains intact over the chosen spatial and temporal scale of analysis, while flows are elements that either enter the system without existing, or exit it without entering. Funds need to be maintained in order to be able to metabolize flows, and the accounting of funds is one of the most essential contributions of MuSIASEM; in fact, many forms of material and energy accounting only consider flows and do not consider the key importance of characterizing the funds needed to reproduce and/or use such flows. Considering a yearly analysis of the energy sector, land use, human activity and power capacity (technology) are examples of funds, while electricity produced and consumed, water consumed and fuels consumed and produced, as well as oil extracted, are examples of flows.

Table 1
MuSIASEM acronyms.
Source: Diaz-Maurin and Giampietro, 2013; Giampietro and Diaz-Maurin, 2014.

Acronym	Description	Acronym	Description
PES	Primary Energy Source	LU	Land Use
EC	Energy Carrier	HH	Household sector
ES	Energy System	TR	Transport sector
El	Electricity	AF	Agriculture & Fishing sector
Fu	Fuels	EM	Energy & Mining sector
He	Heat	SG	Services & Government sector
PC	Power Capacity	MC	Manufacturing & Construction sector
HA	Human Activity	IN	Industry

Recent developments in MuSIASEM have seen the introduction of a new conceptual tool called *processor* (Giampietro, 2018; González-López and Giampietro, 2017; Ripa and Giampietro, 2017; Ripoll-Bosch and Giampietro, 2017), whose aim is to describe the inputs and outputs of flows and funds of a certain process linking it with processes both at the same level and across different levels. Fig. 2 shows an example of a sequential pathway of processors for the fuel chain, starting from oil extraction and ending with transport of fuels to society. Here, the output of one processor becomes an input for the next, and each processor fulfilling a certain function (e.g. “oil extraction”) can be mapped onto different structural processors. Each processor is characterized by a profile of inputs and outputs. Inputs coming from society (produced by processes under human control) are represented at the top of the processor. The useful output, either fulfilling a function for a following processor or being used by society, is represented by the arrow exiting the processor on the right. Inputs from the ecosystem (blue arrows) and outputs to the ecosystem, such as emissions (yellow arrows), are represented at the bottom.

The difference between functional and structural processors is briefly explained in the next sub-section.

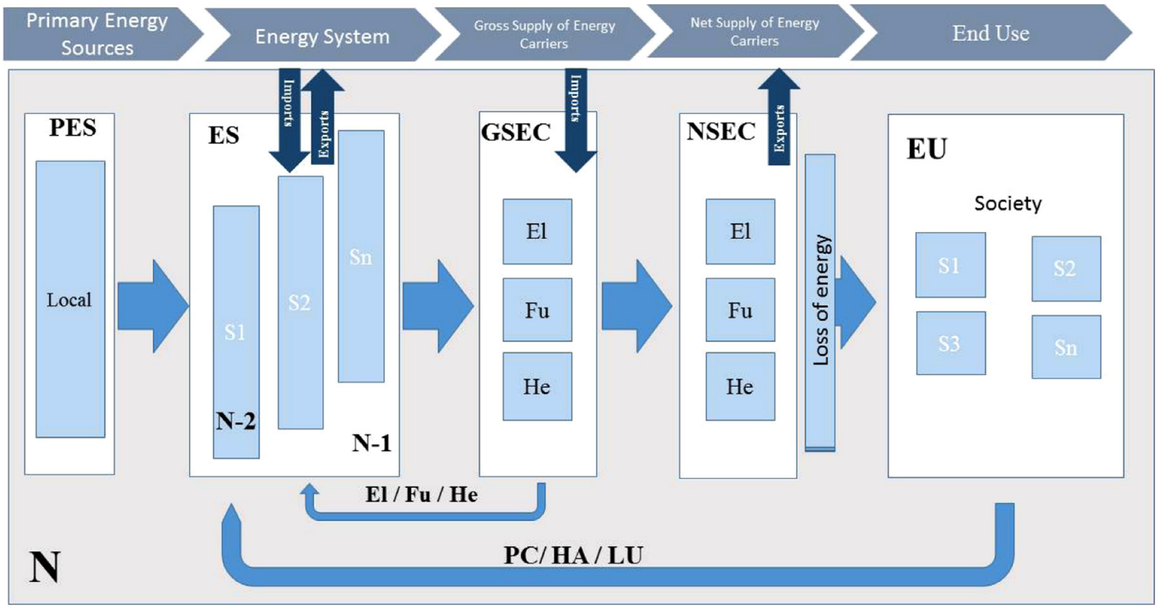

Fig. 1. MuSIASEM's energy grammar.
Source: Diaz-Maurin and Giampietro, 2013; Giampietro and Diaz-Maurin, 2014.

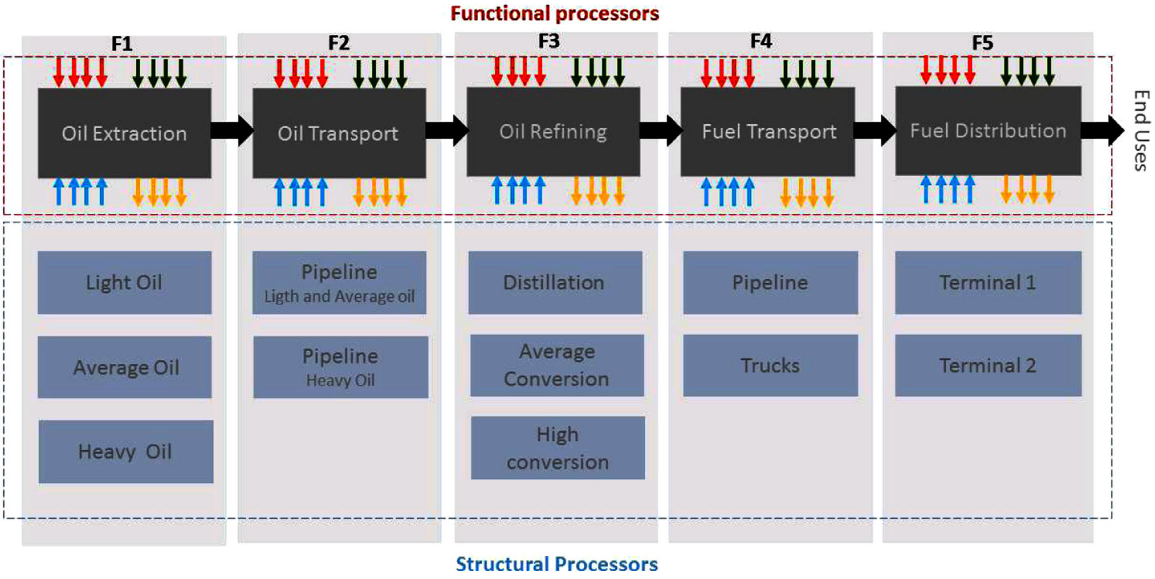

Fig. 2. Sequential metabolic pattern of processors, from oil extraction to end uses.
Source: Own elaboration.

3.2. *Functional and structural elements of oil extraction*

Structural processors describe a process taking place through a specific technology or method, for example oil extraction with deep sea drilling. The characteristics of these processors reflect the technical coefficients determined by the organizational structure of the plant carrying out the process. Functional processors, on the other hand, describe notional elements of a process whose aim is to provide a function within a wider system: for example, fuel refined for the transport system. The characteristics of these processors are defined by the function that has to be expressed to stabilize the metabolism of the larger whole. Theoretical ecology explains the notional definition of a functional processor in terms of mutual information – i.e. a metabolic network (i.e. an ecosystem) defines a virtual image of the metabolic characteristics of the node (network niche) which is independent of the actual characteristics of the metabolic element of the node (Ulanowicz, 1986).

In complex systems organized over different hierarchical levels the definition of the relation over structural and functional elements is case dependent, as it can change according to the level, scale and goal of the analysis. As shown in Fig. 2 of the previous sub-section, different steps within the sequential metabolic pathway of fuels supply fulfill different functions, starting from oil extraction and ending with fuel transport to end uses. Then, for each function different structures expressing it can be identified, depending on the goal of the analysis. In the current study, we focus on the functional processor of oil extraction, singling out the first step shown in Fig. 2. By operating at a lower level of analysis, we split the functional processor of oil extraction into two further sub-functions: extraction of medium oil and extraction of heavy oil, based on the API gravity described in Table 2. This distinction is case dependent, since in Ecuador light oil accounts for less than 1% of total oil extracted, and no extra heavy oil is extracted.

In this case, the functions are not defined at the societal level, but at the next level of organization within which the function of extraction is operating (i.e. at the interface between oil extraction and refinement). Oil products have different functional roles as inputs to refineries, since refineries producing different fuel products require input fuels of different weights. For each sub-function we identify different structures of oil extraction, depending on the amount of Base Sediment Water (BSW) used in the process of extraction. The categorization based on BSW is clarified in Table 3. The four structural types vary depending on the type of oil extracted, and not all types have each structural element – for medium oil in Ecuador, for example, only high BSW and moderate BSW extraction methods are carried out.

The structural distinction based on the amount of BSW is chosen for this case study, as the funds and flows associated with oil extraction are highly dependent on the amount of total fluid (referring to crude oil, water and gas) extracted, and not only on the total amount of crude oil extracted.

Processors are built for each structural element, mapping the input and output flows and funds. In Fig. 3, we zoom in into the current case study to show our chosen functional and structural processors.

The disaggregation between functional and structural types is essential for energy systems, and particularly useful when it comes to generating information for policy making. Being able to characterize energy systems in a modular way both in terms of *what they do* (functions) and *how they do it* (structures) provides us with the fundamental tools needed to tackle current energy problems – this is as crucial as the accounting of both funds (what the system is made of) and flows (what the system does). In fact, many quantitative analyses neglect to address the functionality of system elements that depends on the quantity (size)

Table 2
Classification of oil by API gravity.
Source: Classification of oil by API gravity. Retrieved from http://www.petroleum.co.uk/api.

API gravity(°)	Classification
> 31°	Light oil
22–31°	Medium oil
10–22°	Heavy oil
< 10°	Extra heavy oil

Table 3
Structural categorization based on BSW use.
Source: Own elaboration.

BSW	Structural type
> 90%	Extra high
60–90%	High
30–60%	Moderate
< 30%	Low

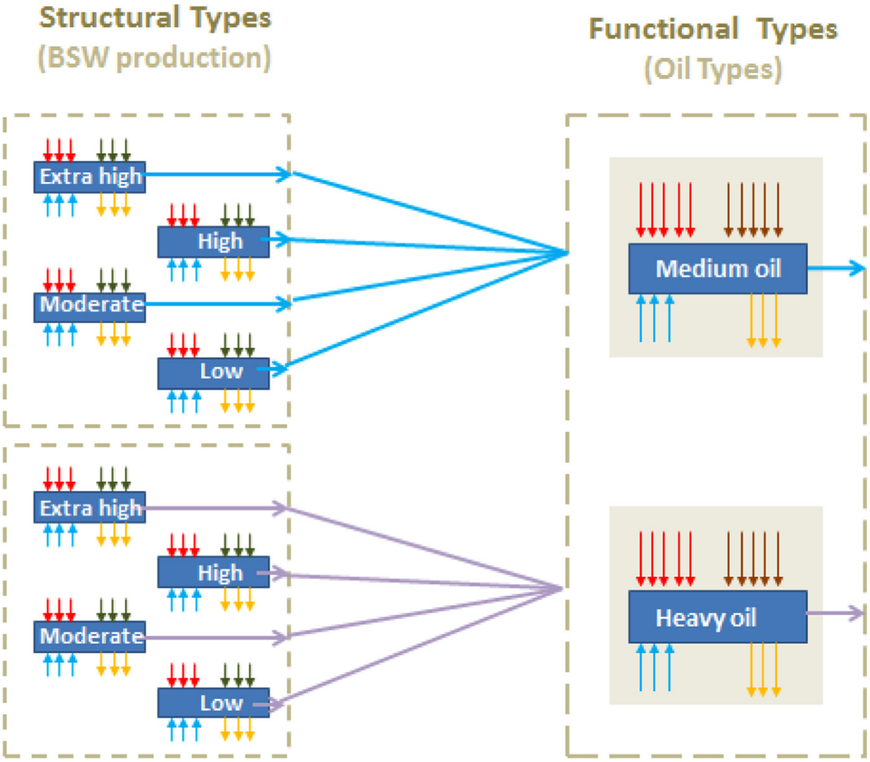

Fig. 3. Structural and functional processors of the case study.
Source: Own elaboration.

and quality (metabolic characteristics) of funds.

3.3. Data

All data presented in the paper refers to 2016 unless stated otherwise. Data for the study was collected both through primary and secondary sources. Ecuador's statistical offices, including ARCH, ARCONEL, PETROAMAZONAS EP and EP PETROECUADOR, provide a detailed overview of oil extraction statistics. Data missing through statistical offices, such as hours of human activity, was calculated by considering the total number of workers, both direct and indirect, and accounting for the amount of hours worked for each type of job (splitting them into administrative jobs and operational jobs) (ARCH, 2016; ARCONEL, 2016; Petroamazonas, 2016; Petroecuador, 2016).

Twenty five interviews with workers at different oil blocks were conducted between March 2016 and March 2017 in order to collect any other useful data missing from national statistics, and to check the coherence of top-down data. Therefore, the final data used in the analysis is considered to be highly reliable, as cross-checks with interviews have allowed confirming top-down statistical information.

4. Results and discussion

4.1. Ecuador's energy system

Table 4 shows an overview of Ecuador's energy system, focusing on primary energy sources (PES) and energy carriers (EC), including imports and exports. As data for 2016 is not available yet, data for 2015 was used, taken from Ecuador's annual energy balance, published by the Ministry of Strategic Sectors (*Ministerio Coordinador de Sectores Estratégicos*, (Ministerio Coordinador de Sectores Estratégicos, 2016)). Oil accounts for almost 90% of the primary energy mix. However, due to a lack of refining capacity, Ecuador is a net exporter of crude oil and net importer of refined fuels.

Leaving electricity aside and focusing on fuels, Table 5 shows the final consumption of fuels by societal sub-sectors, splitting them into GLP, diesel oil, fuel oil and gasoline. The disaggregation of both different fuels and of different societal compartments is needed to characterize end uses and to be able to have a complete overview not only of what is being produced, but also of how and where it is being consumed.

Table 4
PES and EC in Ecuador, 2015 (ktoe).
Source: Own elaboration based on (Ministerio Coordinador de Sectores Estratégicos, 2016).

PES	Total extraction	Imports	Exports	
Crude oil	198,527	N/A	146,620	
Natural Gas	10,029	N/A	N/A	
Biomass	6239	N/A	N/A	
EC	**Total production**	**Imports**	**Exports**	**Final Balance**
Electricity	16,079	44,032	29	60,082
Fuels (incl. GLP)	19,544	48,356	3967	63,933

Table 5
End-use matrix by fuel type.
Source: Own elaboration based on (Ministerio Coordinador de Sectores Estratégicos, 2016).

Sector	GLP TJ	Gasoline TJ	Diesel oil TJ	Fuel oil TJ	Oil TJ
TR	530	111,362	107,871	15,029	–
IN	3296	41	42,455	10,911	–
HH	40,159	–	–	*negl.*	–
SG	2468	–	12,401	828	–
AF	904	4987	–	–	–
MC	6764	46,590	5518	1639	–
EM	860	247	31,657	45,358	15,196
Total	**54,981**	**163,227**	**199,902**	**73,766**	**15,196**

Table 6
Ecuador's extraction blocks classified based on functional oil product.
Source: Own elaboration based on (ARCH, 2016).

# Block	Block		Production (Km3)	% Total production	°API	Type of oil
1	2	GUSTAVO GALINDO	67	0.2	36	Light
2	1	PACOA	2	0.0	33	Light
3	49	BERMEJO	142	0.4	31	Medium
4	64	PALANDA YUCA SUR	124	0.4	24	Medium
5	53	SINGUE	266	0.8	27	Medium
6	60	SACHA	4221	13.2	26	Medium
7	44	PUCUNA	115	0.4	31	Medium
8	56	LAGO AGRIO	224	0.7	29	Medium
9	57	SHUSHUFINDI	6790	21.2	27	Medium
10	58	CUYABENO-TIPISHCA	1534	4.8	26	Medium
11	46	MDC SIPEC	471	1.5	24	Medium
12	47	PBHI	289	0.9	26	Medium
13	52	OCANO - PEÑA BLANCA	138	0.4	23	Heavy
14	12	EDEN YUTURI	2293	7.2	23	Heavy
15	18	PALO AZUL	659	2.1	23	Heavy
16	61	AUCA	3942	12.3	22	Heavy
17	7	COCA PAYAMINO	1874	5.9	22	Heavy
18	10	VILLANO	621	1.9	19	Heavy
19	62	TARAPOA	2016	6.3	21	Heavy
20	45	PUMA	38	0.1	16	Heavy
21	65	PINDO	230	0.7	20	Heavy
22	54	ENO - RON	241	0.8	13	Heavy
23	15	INDILLANA	1683	5.3	20	Heavy
24	21	YURALPA	330	1.0	17	Heavy
25	31	Bloque 31	973	3.0	18	Heavy
26	43	ITT	487	1.5	14	Heavy
27	55	ARMADILLO	13	0.0	13	Heavy
28	59	VINITA	36	0.1	15	Heavy
29	66	TIGUINO	138	0.4	20	Heavy
30	14	NANTU	211	0.7	19	Heavy
31	17	HORMIGUERO	338	1.1	19	Heavy
32	16	IRO	1245	3.9	15	Heavy
33	67	TIVACUNO	211	0.7	19	Heavy
Total			31,962			

4.2. *Building a bottom-up grammar*

In order to build a bottom-up energy grammar, the first step is to characterize the structural and functional elements of the system. Processors are built for each structural element, mapping the input and output flows and funds. In Table 6, extraction blocks in Ecuador are classified based on the type of oil extracted.

Table 7 shows examples of processors for two structural elements: medium oil production with moderate BSW and heavy oil production with high BSW. The same data is collected for all eight structural processors. Data characterizing the inputs and outputs of the processor, as explained previously, are categorized based on the fund-flow model, and based on whether they are internal (coming from and going to the "technosphere") or external (coming from and going to the "biosphere"). From these two examples, we can see that the values of certain flows and funds vary greatly depending on the chosen typology: electricity produced and consumed on site, for example, is almost double the amount when it comes to heavy oil production with high BSW, compared to medium oil production with moderate BSW. Human Activity also shows great variation, with heavy oil production/high BSW requiring four times the amount of human activity per extracted cubic meter, compared to medium oil production/moderate BSW.

What we can see from the characterization of these processors is that extraction of heavy oil with high BSW tends to require a higher input of flows and funds than the extraction of medium oil with moderate BSW. However, the extraction of heavy oil with high BSW tends to be more efficient, as less gas is extracted per unit of oil extracted.

Then, the structural elements are grouped into two functional elements: extraction of medium and heavy oil. Fig. 4 shows how the structural processors are grouped into functional processors based on which percentage of the function is covered by a given structure.

4.3. *Scaling to the overall functional extraction processor*

The three functional processors can now be scaled up forming an overall processor characterizing oil extraction in Ecuador, as shown in Fig. 5, where a further step is added on the right hand side. Table 8 collects the processors for each functional type (medium and heavy oil), their relative weight and the final intensive and extensive processor for oil extraction. The intensive characterization of the processor can then be converted into an extensive one by multiplying its intensive inputs and outputs by the scaling factor, in this case the total amount of oil extracted. Intensive processors are useful as they provide information that can be scaled up or down and used as benchmarks for other countries and case studies, while extensive processors provide an overview of the quantities of flows in the specific case at hand.

This quantitatively simple step is methodologically essential: by upscaling processors from bottom-up structural data, to functional groups, to a final extraction processor, we can simultaneously assess the overall inputs and outputs of the oil extraction sector, and how the individual parts forming this sector contribute to the metabolism. By typologising oil extraction into functional groups, the relative contribution of each type of extraction can be easily checked. From the data shown in Table 8, we can see that over 70% of oil currently extracted in Ecuador is of medium weight. When it comes to flows and funds consumed by the different types of oils, heavy oil is the most intensive both in terms of electricity and fuel consumption.

Considering water use, we saw in Fig. 5 that 65% medium oil uses high or extra high BSW, while over 90% of heavy oil is extracted with high or extra-high BSW. This is reflected in the amount of water needed

Table 7
Examples of flows and funds for three structural processors. *Numbers may not add up due to rounding.*

Processor element	Label	Unit (extensive)		Unit (intensive)		Source
Medium oil production / moderate BSW						
Internal Flow	Electricity auto-consumption	**kWh**	336,685,169	**kWh/m3**	38	(ARCONEL, 2016)
Internal Flow	Fuel for generation	**GJ**	3,605,644	**GJ/m3**	0	(ARCONEL, 2016)
Internal Flow	Fuel oil	**GJ**	185,188	**GJ/m3**	negl.	(ARCONEL, 2016)
Internal Flow	Diesel	**GJ**	2,470,066	**GJ/m3**	0	(ARCONEL, 2016)
Internal Flow	Natural gas	**GJ**	25,225	**GJ/m3**	negl.	(ARCONEL, 2016)
Internal Flow	Oil	**GJ**	925,164	**GJ/m3**	0	(ARCONEL, 2016)
Internal Flow	Fuel for combustion	**GJ**	1,520,544	**GJ/m3**	0	(ARCH, 2016; Parra, 2015)
Internal Flow	Diesel	**GJ**	1,475,853	**GJ/m3**	0	(ARCH, 2016; Parra, 2015)
Internal Flow	Gasoline	**GJ**	44,690	**GJ/m3**	negl.	(ARCH, 2016; Parra, 2015)
Internal Fund	Power Capacity	**kW**	107,267	**kW/m3**	0.012	(ARCONEL, 2016; Asamblea Nacional, 2010)
Internal Fund	Human activity	**hours**	10,533,235	**hours/m3**	1	(MICSE, 2016)
External Inflow	Fluid	**m3**	17,384,787	**m3/m3**	2	(ARCH, 2016)
External Inflow	Raw water	**m3**	1,193,902	**M3/m3**	0	(ARCH, 2016)
External Outflow	Water for reinjection	**m3**	8,608,485	**m3/m3**	1	(ARCH, 2016)
External Outflow	Gas to burn	**m3**	184,500,504	**m3/m3**	21	(ARCH, 2016)
External Outflow	CO2	**kg**	250,368,078	**kg/m3**	29	(Parra, 2015)
Output	Medium oil	**m3**	**8,776,302**	**m3**	**8,776,302**	(ARCH, 2016)
Heavy oil production / high BSW						
Internal Flow	Electricity auto-consumption	**kWh**	358,785,629	**kWh/m3**	100	(ARCONEL, 2016)
Internal Flow	Fuel for generation	**GJ**	4,733,479	**GJ/m3**	1	(ARCONEL, 2016)
Internal Flow	Diesel	**GJ**	1,652,736	**GJ/m3**	1	(ARCONEL, 2016)
Internal Flow	Natural gas	**GJ**	2,206,094	**GJ/m3**	1	(ARCONEL, 2016)
Internal Flow	Oil	**GJ**	874,649	**GJ/m3**	0	(ARCONEL, 2016)
Internal Flow	Fuel for combustion	**GJ**	967,515	**GJ/m3**	0	(ARCH, 2016; Parra, 2015)
Internal Flow	Diesel	**GJ**	942,210	**GJ/m3**	0	(ARCH, 2016; Parra, 2015)
Internal Flow	Gasoline	**GJ**	25,304	**GJ/m3**	negl.	(ARCH, 2016; Parra, 2015)
Internal Fund	Power Capacity	**kW**	150,019	**kW/m3**	0.043	(ARCONEL, 2016; Asamblea Nacional, 2010)
Internal Fund	Human activity	**hours**	15,247,448	**hours/m3**	4	(MICSE, 2016)
External Inflows	Fluid	**m3**	23,440,806	**m3/m3**	7	(ARCH, 2016)
External Inflows	Raw water	**m3**	569,752	**m3/m3**	0	(ARCH, 2016)
External Outflows	Water for reinjection	**m3**	19,860,977	**m3/m3**	6	(ARCH, 2016)
External Outflows	Gas to burn	**m3**	53,025,635	**m3/m3**	15	(ARCH, 2016)
External Outflows	CO2	**kg**	306,809,266	**kg/m3**	86	(Parra, 2015)
Output	Heavy oil	**m3**	**3,579,828**	**m3**	**3,579,828**	(ARCH, 2016)

for reinjection, which is considerably higher for heavy oil compared to medium. It's important to note that this is because of the structural processors used now to extract heavy oil, and not necessarily because heavy oil produces more BSW per se. This multiscale analysis makes it possible to predict the effect of different combinations of lower level typologies of processors, which is useful for scenario building as we will see in the next section.

Looking at Ecuador's 2016 metabolic pattern for oil extraction, we can see that:

- On average, over 100 kWh of electricity are needed for each cubic meter of crude oil extracted;
- Approximately 1.5 GJ of fuels are consumed for each cubic meter of crude oil extracted: most of them (1.3 GJ) are used to generate electricity on site, and the rest to operate machinery;
- As for funds, approximately 0.032 kW of power capacity are needed for each cubic meter of crude oil extracted; and 2 h of human activity, including both direct (operational) and indirect (administrative) jobs;
- Considering water use, almost 8 m^3 of fluid (water, gas and oil) are extracted for each cubic meter of oil recovered – 0.2 m^3 of freshwater are consumed per unit of extraction, and almost 6 m^3 of water are reinjected;
- Finally, the oil extraction step contributes to overall CO_2 emissions by producing almost 84 kg of CO_2 per cubic meter of oil extracted.

This framework is useful for two purposes. Firstly, it allows us to have a detailed description of the flows and the funds consumed by Ecuador's oil extraction sector, as briefly outlined, identifying the relevant elements of the system. Given the lack of data on this step of the fuel chain, the metabolic description is valuable for energy analyses. Secondly, the characterization of these elements in the form of processors allows checking how the combination of various elements of the oil extraction process contributes to its final metabolism, and how changing the relative weight of the elements affects the flows and funds of the final oil extraction processor, as will be seen in the next subsection.

4.4. Building scenarios: Ecuador's projected five year increase in oil extraction

The modular framework proposed is particularly useful when it comes to building scenarios relevant to policy decisions. It is important to note that, within MuSIASEM, a scenario is not meant to be a detailed dynamic model predicting what will happen in the future. Rather, scenarios are ways to check whether there are constraints on proposed policies or desired future states by checking the feasibility and viability of proposed changes (Giampietro et al., 2014) and establishing relations over expected profiles of different flows and funds. In this way, the analysis of scenarios is made by looking at patterns rather than focusing on an individual dimension at the time. In this case, we check how Ecuador's oil extraction metabolism will change if the current trends in oil extraction continue over the next five years and follow the country's main extraction policies, as outlined in the Introduction. Fig. 6 shows the increased delta of production that is expected in Ecuador over the next five years (Table 9).

In order to build the scenario, we follow four steps:

1) The expected growth in oil extraction in Ecuador over the next five years is identified. Considering the increase in productivity of the 2016 blocks, and the development of new exploratory blocks, such as the OGLAN B28, B79 and B83, oil extraction is expected to grow

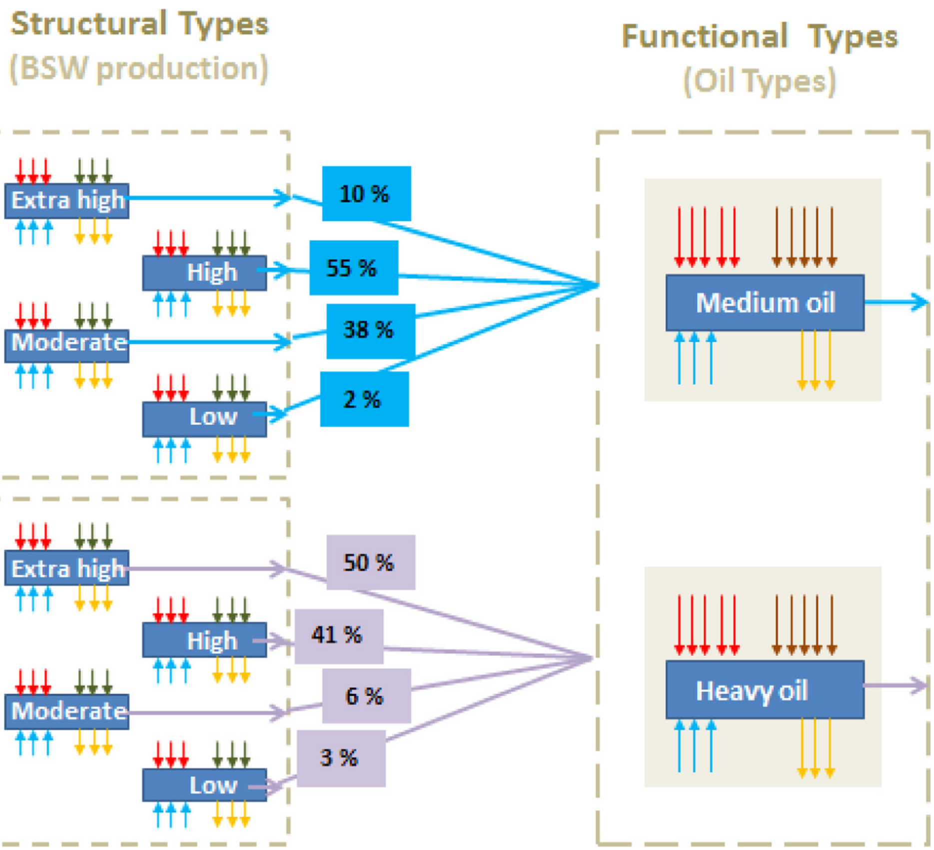

Fig. 4. Scaling of structural processors into functional ones.
Source: Own elaboration.

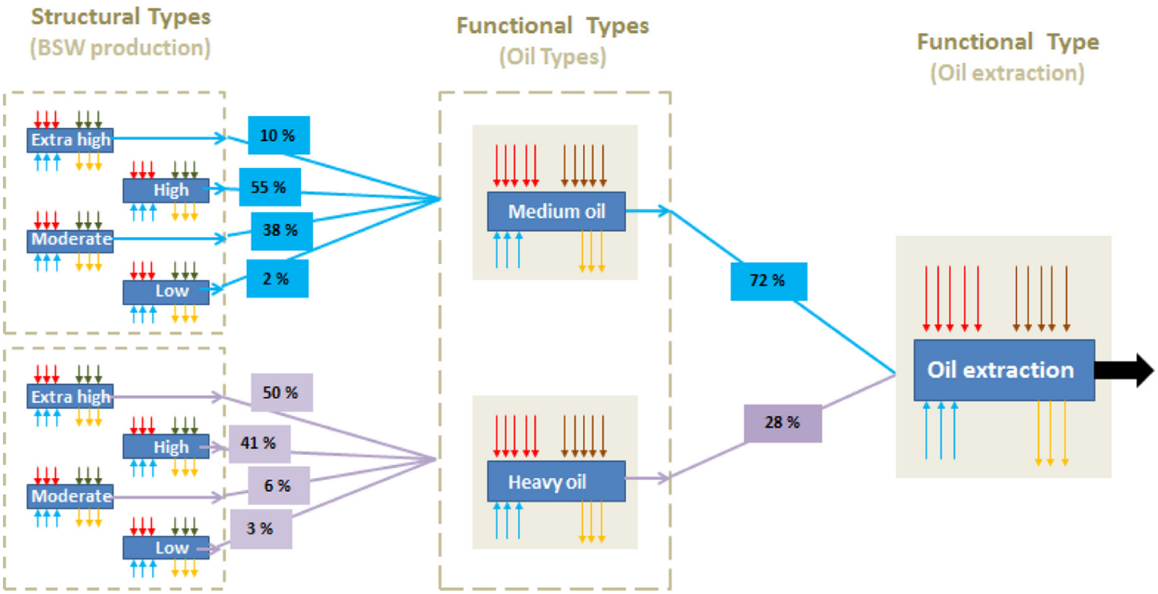

Fig. 5. Scaling functional processors to the final oil extraction one.
Source: Own elaboration

by approximately 20 million cubic meters (Secretaria de Hidrocarburos, 2016a). For this scenario, only the increase in production of blocks operating in 2016 was considered. This leads to an increased delta of production of over 12 million cubic meters. The production up to 2016 levels is assumed to remain static – so the change in structural and functional elements is only applied to the delta of production;

2) The main blocks associated with the expected growth are identified and grouped following the same classification as in the diagnostic (Fig. 3);
3) This allows checking how the increased delta of production will be covered: it is estimated that 35% of the delta will be covered by medium oil, with blocks such as Auca, Cuyabeno, Shushufindi and Sacha being the most representative. The remaining 65% will be

Table 8
Building the final oil extraction processor. *Numbers may not add up due to rounding.*
Source: Own elaboration.

Processor elements	Label	Unit	Medium oil	Heavy oil	% Medium oil	% Heavy oil	Intensive processor		Extensive processor	
							Unit	Value	Unit	Value
Internal flow	Electricity auto-consumption	**kWh/m^3**	71	207	72	28	**kWh/m^3**	108	**kWh**	3,460,046,334
Internal flow	Fuel for generation	**GJ/ m^3**	0.8	3	72	28	**GJ/ m^3**	1.3	**GJ**	41,490,482
Internal flow	Fuel oil	**GJ/ m^3**	negl.	negl.	72	28	**GJ/ m^3**	negl.	**GJ**	193,461
Internal flow	Diesel	**GJ/ m^3**	0.3	0.8	72	28	**GJ/ m^3**	0.0.4	**GJ**	13,501,833
Internal flow	Natural gas	**GJ/ m^3**	0.2	0.7	72	28	**GJ/ m^3**	0.3	**GJ**	10,772,120
Internal flow	Oil	**GJ/ m^3**	0.3	1	72	28	**GJ/ m^3**	0.5	**GJ**	17,023,068
Internal flow	Fuel for combustion	**GJ/ m^3**	0.2	0.3	72	28	**GJ/ m^3**	0.2	**GJ**	7239,488
Internal flow	Diesel	**GJ/ m^3**	0.2	0.2	72	28	**GJ/ m^3**	0.2	**GJ**	6195,163
Internal flow	Gasoline	**GJ/ m^3**	negl.	negl.	72	28	**GJ/ m^3**	negl.	**GJ**	270,924
Internal flow	Natural gas	**GJ/ m^3**	negl.	negl.	72	28	**GJ/ m^3**	negl.	**GJ**	773,401
Internal fund	Power Capacity	**kW/ m^3**	21.3	60	72	28	**kW/m^3**	0.032	**kW**	1022,157
Internal fund	Human activity	**hours/ m^3**	1.6	3.4	72	28	**hours/ m^3**	2	**hours**	67,470,065
External inflow	Fluid	**m^3/ m^3**	4	14	72	28	**m^3/ m^3**	7	**m^3**	216,408,201
External inflow	Raw water	**m^3/ m^3**	0.2	0.2	72	28	**m^3/ m^3**	0.2	**m^3**	7199,532
External outflow	Water for reinjection	**m^3/ m^3**	3	13	72	28	**m^3/ m^3**	6	**m^3**	184,497,642
External outflow	Gas to burn	**m^3/ m^3**	36	13	72	28	**m^3/ m^3**	30	**m^3**	957,030,364
External outflow	CO_2	**kg/ m^3**	54	161	72	28	**kg/ m^3**	84	**kg**	2666,028,197
Output	Oil production	**m^3**	23,044,086	8797,248			**m^3**	3,1910,559		

   covered by heavy oil, with blocks such as ITT, Tarapoa and Villano;
4) Having identified the functional elements, and their relative structural components, we can scale up the processors found in the previous section to check what flows and funds will be needed to increase the delta in production.

Fig. 7 shows how the scaling factors used in the diagnostic change in this scenario. It is important to note that this only applies to the increased delta of extraction, and not for total extraction over the next five years. It can be seen that medium oil extraction will be covered only with high and moderate BSW production.

By changing the relative weight of the processors, we can generate a *simulated processor* required for the delta of increased production (Table 8). It can be seen that, due to a shift to heavy oil, and a shift in the structural elements of both heavy and medium oil, the processor is different from that of current oil extraction. This is why disaggregation at lower levels is important when building scenarios, as simple input/output analyses disregard changes taking place across different levels. What we see in this case is that, due to the change in profile of structural elements, the extraction processor for the increased delta of production consumes less water, fuels and electricity than the current extraction processor. This may seem counterintuitive, as 65% of the delta of production is covered by heavy oil, but the decrease is due to the change in the structural contributions of the heavy oil: only 20% of it is covered by high and extra-high BSW production. In general, newer blocks of extraction tend to be more efficient and are associated with lower BSW production – this is why the increased delta, which will be covered by exploiting new blocks, will on average consume less flows and funds than current extraction.

It is important to note that we are only talking about the delta. To have a complete overview of how the extraction process will change, we should assess how the processors of the structural elements currently being used will change over time. It is expected that as blocks age, their structure also changes, moving towards a higher production of BWS. Thus, we can expect that the improvement in the extraction of the oil in the delta – in terms of the profile of inputs required per unit of production – will be more than compensated in negative terms by the progressive reduction of the quality of the blocks in production. This

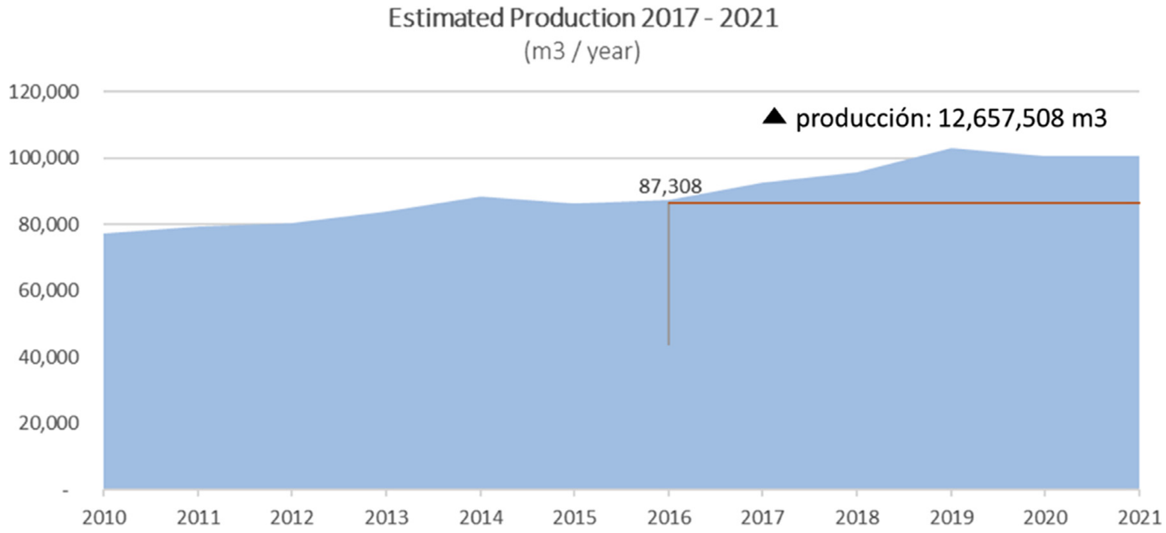

Fig. 6. Ecuador's increased production delta over the next five years.
Source: (Secretaria de Hidrocarburos, 2016b).

Table 9
Identified blocks to cover the increased delta in production.
Source: Own elaboration.

BLOCK		**Functional Processor** Oil Types	**Structural Processor** Water production
#	Name	°API	% BSW
0	-	Ligth Oil (> 31 °)	Extra High (> 90%)
1	PACOA		High (60–90%)
0	-		Moderate (30–60%)
1	GUSTAVO GALINDO		Low (< 30%)
2	BERMEJO,EDEN YUTURI	Medium Oil (22–31°API)	Extra High (> 90%)
7	SINGUE,SHUSHUFINDI, CUYABENO,PALANDA,MDC, PALO AZUL,COCA PAYAMINO		High (60–90%)
5	SACHA,PUCUNA,LAGO AGRIO,PBHI,AUCA		Moderate (30%-60%)
1	OCANO - PEÑA BLANCA		Low (< 30%)
5	TARAPOA,YURALPA,VILLANO,IRO,TIVACUNO	Heavy Oil (< 22°API)	Extra High (> 90%)
7	PINDO,31,INDILLANA,ARMADILLO,TIGUINO,NAMTU,HORMIGUERO,		High (60–90%)
3	VINITA,PUMA,ITT		Moderate (30%-60%)
1	ENO-RON		Low (< 30%)

aspect is crucial for future studies.

Focusing solely on the increased delta of production over the five-year period, we can see that the growth of oil extracted will require an additional 800 MW of power capacity, almost 40 million hours of human activity (about 4500 jobs per year during the period), over 25 TJ of fuels and over 1 million MWh of electricity. However, this information is not relevant if we do not assess the effect that the ageing of blocks will have on the baseload of production, and needs to be interfaced with Multi-Criteria Analyses (MCA) in order to be operationalized for decision-making. Both these aspects will be addressed in future studies, as outlined in our conclusions.

5. Conclusions and policy recommendations

In this paper, we have proposed a methodological framework to describe the oil extraction process, using MuSIASEM and the concept of processors to analyze the relation between functional and structural elements of the energy system. We then applied the methodology to the case of Ecuador. As extraction in Ecuador is not as globally relevant as in other Latin American countries, we could focus on a smaller scale by collecting detailed data from individual extraction blocks. However, in spite of the small relative contribution of Ecuador to the global oil extraction system, the chosen case study is not irrelevant: firstly, it shows that with this method it is possible to generate policy relevant information – for instance, at the national level oil extraction is gaining increasing importance in Ecuador's policies and economic outlook, and the data presented here can help in making informed decisions on the funds and flows needed for materializing that increase in extraction. Secondly, the integrated set of relations of processors built bottom-up with data from Ecuador can be adjusted and applied to other countries, by using dictionaries describing the characteristics of the processors in different contexts, as oil extraction technologies and methods can be generalized.

The results for Ecuador showed that currently medium oil dominates the market, and that at the moment the extraction process on average requires, per cubic meter of oil extracted, over 100 kWh of electricity, 1.5 GJ of fuels, 3 kW of power capacity, 2 h of human activity and 6.2 m^3 of freshwater, of which 6 m^3 are reinjected. The extraction process also generates, per cubic meter of oil extracted, almost 85 kg of CO_2 emissions. The package of indicators that are generated by

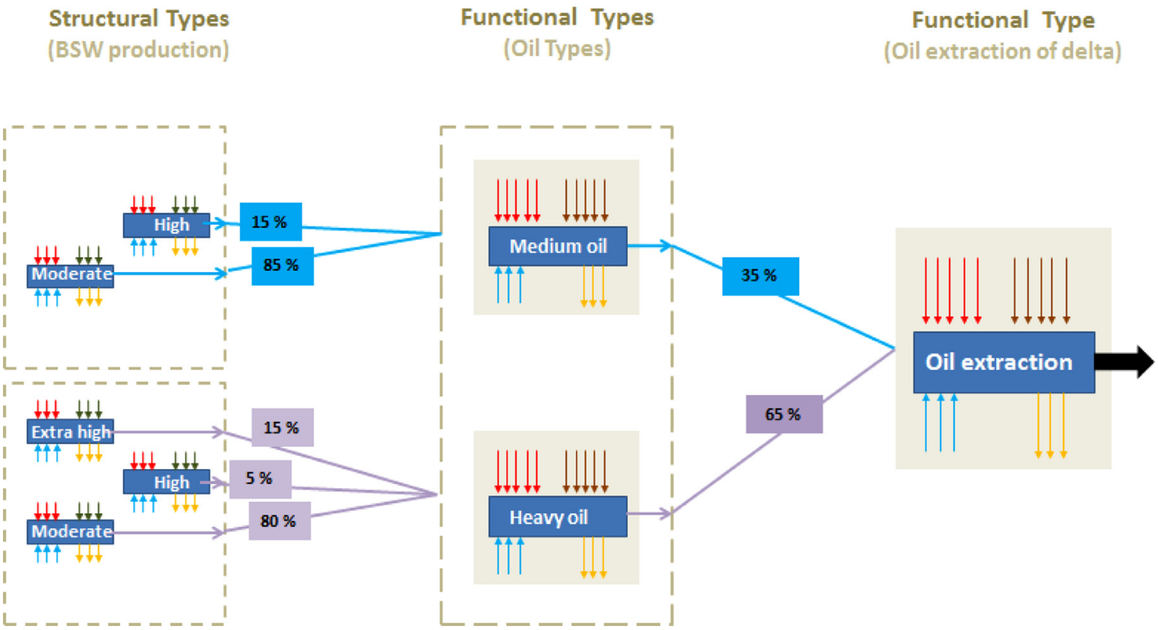

Fig. 7. Scaling of processors for the increased delta of production.
Source: Own elaboration.

the approach allows providing an integrated assessment of the performance of the investigated process in the form of a multi-criteria analysis. For example: (i) the profile of inputs of energy carriers (electricity, and fuels) are relevant for calculating the Energy Return on the Energy Investment (mapping both on the speed of depletion of the stock of resources and on emissions of CO2 per net supply); (ii) the requirement of power capacity (technology) is an indicator relevant for assessing the fixed economic costs; (iii) the requirement of labor is relevant both for assessing the economic costs and the opportunity for employment; (iv) the information about freshwater and CO2 emissions is relevant for an analysis of environmental impact. Future work will focus on organizing this information in the form of a Multi-Criteria Analysis in order to make it available to decision makers in the form of a decision support system

The analysis of the proposed scenario showed that extraction of new oil resources in Ecuador will shift from medium to heavy oil, but as this will be done mostly within newer blocks, less Base Sediment Water (BSW) will be produced in the process. This will lower the requirement of inputs per unit of oil produced. However, in order to provide a full overview of the overall effect on Ecuador's oil extraction metabolism, a time dimension must be introduced in the analysis, checking how processors of the current oil extraction structures will change as they age in terms of flows and funds consumed. It is well known that, in general, older blocks consume more resources. This explains why the simulated processor focusing only on the delta of increased production, based on the exploitation of new blocks, is less energy and water intensive than Ecuador's 2016 real processor. Thus, the inclusion of a time dimension to the analysis is identified as a second area for further research.

Acknowledgements

JRM acknowledges support from the project HAR2016–76814-C2-1-P AEI/FEDER, UE, Spanish Ministry of Economy and Competitiveness. LJDF and MG have received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no 689669 (MAGIC). The Institute of Environmental Science and Technology (ICTA) has received financial support from the Spanish Ministry of Economy and Competitiveness through the "María de Maeztu" program for Units of Excellence (MDM-2015-0552). This work reflects the authors' view only; the funding agencies are not responsible for any use that may be made of the information it contains.

References

Ali, B., Kumar, A., 2017. Life cycle water demand coefficients for crude oil production from five North American locations. Water Res. 123, 290–300. https://doi.org/10.1016/j.watres.2017.06.076.

Aragão, A., Giampietro, M., 2016. An integrated multi-scale approach to assess the performance of energy systems illustrated with data from the Brazilian oil and natural gas sector. Energy 115, 1412–1423. https://doi.org/10.1016/j.energy.2016.06.058.

ARCH, 2016. Bases estadísticas del sector petrolero [WWW Document].

ARCONEL, 2016. Bases estadísticas del sector eléctrico.

Asamblea Nacional, 2010. Proyecto de Ley Reforma a la Ley de Hidrcarburos Tr. 87580.

Ayres, R.U., 1995. Life cycle analysis: a critique. Resour. Conserv. Recycl. 14, 199–223. https://doi.org/10.1016/0921-3449(95)00017-D.

Brandt, A.R., Dale, M., Barnhart, C.J., 2013a. Calculating systems-scale energy efficiency and net energy returns: a bottom-up matrix-based approach. Energy 62, 235–247. https://doi.org/10.1016/j.energy.2013.09.054.

Brandt, A.R., Englander, J., Bharadwaj, S., 2013b. The energy efficiency of oil sands extraction: Energy return ratios from 1970 to 2010. Energy 55, 693–702. https://doi.org/10.1016/j.energy.2013.03.080.

Bravo, E., 2007. Los impactos de la explotación petrolera en ecosistemas tropicales y la biodiversidad. Front. Comunes Y. Asoc. Ecológica St. Tomás 1–36.

Chang, Y., Huang, R., Ries, R.J., Masanet, E., 2014. Shale-to-well energy use and air pollutant emissions of shale gas production in China. Appl. Energy 125, 147–157. https://doi.org/10.1016/j.apenergy.2014.03.039.

Chen, Y., Feng, L., Wang, J., Höök, M., 2017. Emergy-based energy return on investment method for evaluating energy exploitation. Energy 128, 540–549. https://doi.org/10.1016/j.energy.2017.04.058.

Cordes, E.E., Jones, D.O.B., Schlacher, T.A., Amon, D.J., Bernardino, A.F., Brooke, S., Carney, R., DeLeo, D.M., Dunlop, K.M., Escobar-Briones, E.G., Gates, A.R., G?nio, L., Gobin, J., Henry, L.-A., Herrera, S., Hoyt, S., Joye, M., Kark, S., Mestre, N.C., Metaxas, A., Pfeifer, S., Sink, K., Sweetman, A.K., Witte, U., 2016. Environmental impacts of the deep-water oil and gas industry: a review to guide management strategies. Front. Environ. Sci. 4, 58. https://doi.org/10.3389/fenvs.2016.00058.

Court, V., Fizaine, F., 2017. Long-Term estimates of the energy-return-on-investment (EROI) of coal, oil, and gas global productions. Ecol. Econ. 138, 145–159. https://doi.org/10.1016/j.ecolecon.2017.03.015.

Diaz-Maurin, F., Giampietro, M., 2013. A "Grammar" for assessing the performance of power-supply systems: Comparing nuclear energy to fossil energy. Energy 49, 162–177. https://doi.org/10.1016/j.energy.2012.11.014.

EP Petroecuador, 2012. Resolución Directori N°. DIR-EPP-01-2012-01-16 de 16 de enero de 2012.

Fontaine, G., 2003. Petróleo y desarrollo sostenible en Ecuador. FLACSO, Sede Ecuador, Quito, Ecuador.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge, Massachusetts.

Georgescu-Roegen, N., 1970. The economics of production. Am. Econ. Rev. 60, 2.

Giampietro, M., 2018. Anticipation in agriculture. In: Handbook of Anticipation. Springer International Publishing, Cham, pp. 1–35. https://doi.org/10.1007/978-3-319-31737-3_23-1.

Giampietro, M., 2003. Multi-Scale Integrated Analysis of Agro-ecosystems, Crop Science, Advances in Agroecology. CRC Press, Boca Raton. https://doi.org/10.2135/cropsci2006.0003br.

Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F., 2014a. Resource Accounting for Sustainability Assessment: the Nexus between Energy, Food, Water and Land Use, Resource Accounting for Sustainability Assessment: the Nexus between Energy, Food, Water and Land Use. Routledge, Abingdon. https://doi.org/10.4324/9781315866895.

Giampietro, M., Diaz-Maurin, F., 2014b. The Energy Grammar. In: Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F. (Eds.), Resource Accounting for Sustainability: The Nexus between Energy, Food, Water and Land Use. Routledge, Abingdon, pp. 90–115.

Giampietro, M., Mayumi, K., 2000. Multiple-scale integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales. Popul. Environ. 22, 155–210.

Giampietro, M., Mayumi, K., Ramos-Martin, J., 2013. Two conceptual tools for multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): 'Multi-purpose grammars' and 'impredicative loop analysis,' Beyond Reductionism: A Passion for Interdisciplinarity. 10.4324/9780203112281.

Giampietro, M., Mayumi, K., Ramos-Martin, J., 2009. Multi-scale integrated analysis of societal and eco system metabolism (MuSIASEM): theoretical concepts and basic rationale. Energy 34, 313–322. https://doi.org/10.1016/j.energy.2008.07.020.

Giampietro, M., Mayumi, K., Sorman, A.H., 2011. The metabolic pattern of societies: where economists fall short. Routledge, Abingdon.

González-López, R., Giampietro, M., 2018. Relational analysis of the oil and gas sector of Mexico: implications for Mexico's energy reform. Energy 154, 403–414. https://doi.org/10.1016/j.energy.2018.04.134.

González-López, R., Giampietro, M., 2017. Multi-scale integrated analysis of charcoal production in complex Social-ecological systems. Front. Environ. Sci. 5. https://doi.org/10.3389/fenvs.2017.00054.

Hollanda, L., Castello Branco, R., Lins, C., Morais, R., 2016. The geopolitics of oil and gas: the role of Latin America. Energy Geopolit. Role Lat. Am. 40.

Horne, R., Grant, T., Verghese, K., 2009. Life Cycle Assessment: Principles, Practice and Prospects. CSIRO Publishing, Clayton South, Australia.

International Energy Agency, 2017. World Energy Balances 2017.

Lazzaroni, E.F., Elsholkami, M., Arbiv, I., Martelli, E., Elkamel, A., Fowler, M., 2016. Energy infrastructure modeling for the oil sands industry: current situation. Appl. Energy 181, 435–445. https://doi.org/10.1016/j.apenergy.2016.08.072.

MICSE, 2016. Ministerio Coordinador de Sectores Estratégicos. Agenda Nacional de la Energía 2016–2040 80.

Ministerio Coordinador de Sectores Estratégicos, 2016. Balance Energético Nacional. https://doi.org/10.1017/CBO9781107415324.004.

Ministerio de Comercio Exterior, 2016. Informe de Gestión 2016. Quito, Ecuador.

Murphy, D.J., Hall, C.A.S., 2011. Energy return on investment, peak oil, and the end of economic growth. Ann. N. Y. Acad. Sci. 1219, 52–72. https://doi.org/10.1111/j.1749-6632.2010.05940.x.

Nimana, B., Canter, C., Kumar, A., 2015. Energy consumption and greenhouse gas emissions in the recovery and extraction of crude bitumen from Canada's oil sands. Appl. Energy 143, 189–199. https://doi.org/10.1016/j.apenergy.2015.01.024.

Owen, N.A., Inderwildi, O.R., King, D.A., 2010. The status of conventional world oil reserves-Hype or cause for concern? Energy Policy 38, 4743–4749. https://doi.org/10.1016/j.enpol.2010.02.026.

Parra, R., 2015. Energy demand in the oil extraction system in Ecuador. In: Kordas, O., Ulgiati, S., Schnitzer, H., Casazza, M., Braunegg, S. (Eds.), Energy and Urban Systems. Proceedings of the 9th Biennial International Workshop "Advances in Energy Studies." Verlag der Technischen Universität Graz, Graz, p. 51.

Pastore, G., Giampietro, M., Mayumi, K., 2000. Societal metabolism and multiple-scale integrated assessment: empirical validation and examples of application. Popul. Environ. 22, 211–254.

Peralta-Ruiz, Y., González-Delgado, A.-D., Kafarov, V., 2013. Evaluation of alternatives for microalgae oil extraction based on exergy analysis. Appl. Energy 101, 226–236. https://doi.org/10.1016/j.apenergy.2012.06.065.

Petroamazonas, 2016. Oil production reports in blocks.

Petroecuador, 2016. Información estadística [WWW Document].

Poddar, T., Jagannath, A., Almansoori, A., 2017. Use of reactive distillation in biodiesel production: a simulation-based comparison of energy requirements and profitability indicators. Appl. Energy 185, 985–997. https://doi.org/10.1016/j.apenergy.2015.12.054.

Rajagopal, D., Sexton, S.E., Roland-Holst, D., Zilberman, D., 2007. Challenge of biofuel: filling the tank without emptying the stomach? Environ. Res. Lett. 2, 044004. https://doi.org/10.1088/1748-9326/2/4/044004.

Rathmann, R., Szklo, A., Schaeffer, R., 2010. Land use competition for production of food and liquid biofuels: an analysis of the arguments in the current debate. Renew. Energy 35, 14–22. https://doi.org/10.1016/j.renene.2009.02.025.

Ripa, M., Giampietro, M., 2017. Report on Nexus Security using Quantitative Story-Telling MAGIC (H2020–GA 689669) Project Deliverable 4.1. Bellaterra.

Ripoll-Bosch, R., Giampietro, M., 2017. D4.2 Report on EU socio-ecological systems (magic nexus project). Bellaterra.

Rodríguez, G.A., 1998. Petróleo y conflictos sociambientales: El caso de Pastaza, bloque número 10, In: LASA XXI International Congress. Chicago.

Secretaria de Hidrocarburos, 2016a. Estadistica Hidrocarburifera de Petroleo Crudo.

Secretaria de Hidrocarburos, 2016b. Average National Oil Production-Estimates 2016–2030.

Ulanowicz, R.E., 1986. Growth and Development: Ecosystem Phenomenology. Springer, New York.

Vallejo, M.C., Burbano, R., Falconí, F., Larrea, C., 2015. Leaving oil underground in Ecuador: the Yasuní-ITT initiative from a multi-criteria perspective. Ecol. Econ. 109, 175–185. https://doi.org/10.1016/j.ecolecon.2014.11.013.

Velasco-Fernandez, R., Ramos-Martin, J., Giampietro, M., 2015. The energy metabolism of China and India between 1971 and 2010: studying the bifurcation. Renew. Sustain. Energy Rev. 41, 1052–1066. https://doi.org/10.1016/j.rser.2014.08.065.

Vidic, R.D., Brantley, S.L., Vandenbossche, J.M., Yoxtheimer, D., Abad, J.D., 2013. Impact of shale gas development on regional water quality. Science 340. https://doi.org/10.1126/science.1235009.

World Energy Council, 2016. World energy resources. World Energy Counc. Rep. 1, 468. ⟨http://www.worldenergy.org/wp-content/uploads/2013/09/Complete_WER_2013_Survey.pdf⟩.