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Exploration of the environmental implications of ageing conventional oil reserves with relational analysis

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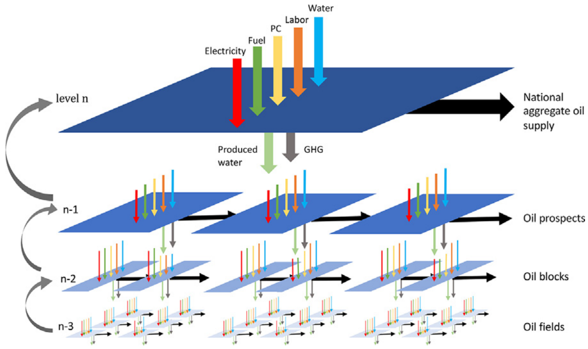
HIGHLIGHTS

- The versatility of relational analysis to assess oil exploitation is demonstrated.
- Conventional oil extraction in Ecuador in 1972–2018 serves as illustrative case.
- Performance is assessed across hierarchical scales and dimensions of analysis.
- Changes in GHG emission and water flows with ageing of oil fields are highlighted.
- Combined with multi-criteria analysis it can be used for decision support.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel method based on relational analysis is presented for assessing the performance of conventional oil exploitation and its environmental implications, with a focus on the energy-water nexus. It considers the energy system as a metabolic network and integrates various factors relevant for technical, economic and environmental processes, thus avoiding some of the simplifications inherent in conventional approaches to the assessment of primary resource quality, such as economic cost-benefit analysis (CBA) and the energy return on investment (EROI). Relational analysis distinguishes between functional (notional) and structural (tangible) elements in the metabolic network, which allows a simultaneous characterization and geo-localization of the exploitation process across different scales and dimensions of analysis. Key aspects of the approach are illustrated with data from the Ecuadorian oil sector spanning the period 1972–2018. It is shown that by establishing a relation among the characteristics of the exploited oil fields (oil typology, age of field) and those of the exploitation process (requirement of energy carriers, labor, freshwater and power capacity and generation of greenhouse gases and oil-produced water), changes in the performance and environmental implications of the oil extraction system can be characterized at different points in space and time.

1. Introduction

The transition from fossil to renewable energy sources is hot on the political agenda of governments worldwide (European Commission, 2019; United Nations, 2019). The scale and the pace of the transition are key factors in achieving this political ambition (Solé et al., 2018). Indeed, the clean energy transition is not simply a question of substituting

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non-renewable with renewable primary energy sources, but requires enormous dedicated investments of energy and raw materials to enable the transition process (e.g., for the building of renewable power capacity and related infrastructures, replacing the car fleet and other forms of power capacity). Investments in the development of alternative energy sources will have to compete for resources with other economic sectors, such as production of food and products and services that are directly linked to maintaining our current standard of living (Bhattacharyya and Timilsina, 2009; de Blas et al., 2019). Hence, meeting this increased energy requirement during the transition period (on top of that implied by population growth) is a major challenge as the quality of the remaining fossil energy sources is rapidly and progressively declining (Mohr et al., 2015). Little is known about the amount of net energy that could potentially be extracted from the remaining fossil energy sources and at what pace, nor about the consequences of the ageing of oil wells on the environment. While the energy-emissions trap has recently drawn the attention of the scientific community (Capellán-Pérez et al., 2019; Gavenas et al., 2015; Masnadi and Brandt, 2017; Sers and Victor, 2018), the energy-water nexus of conventional oil exploitation has been largely ignored (McIntosh and Ferguson, 2019).

Yet water plays a significant role in conventional oil production, notably in the extraction phase. Conventional oil is extracted using primary, secondary, or tertiary recovery methods. Primary recovery is used in the first stage, when natural pressures in the oil reservoir are sufficient to bring oil to the surface. Secondary recovery, also known as water flooding, is practiced as reservoir pressure falls. Water is injected through separate injection wells located in formations that have fluid communication with the production well to maintain reservoir pressure. In tertiary recovery, also referred to as enhanced oil recovery, thermal methods are used to recover the remaining oil, such as steam or gas injection or chemical flooding, sometimes using wells used earlier in secondary recovery (Tiedeman et al., 2016).

Finally, an oil well does not only yield oil, but also gaseous hydrocarbons and produced water. Produced water may originate as natural water in the formations holding hydrocarbons (and water moving in from adjacent aquifers/formations during primary recovery) or water injected in the formation as part of the extraction process (water and steam flooding). Produced water contains variable amounts of chemicals, metals, and sediments, depending on the natural chemical characteristics of the formation and the recovery techniques used. This entails that its disposal is a major environmental and health concern (AlAnezi et al., 2013; Campos and Nonato, 2018; Harati, 2012; San Sebastián and Hurtig, 2004; Yusta-García et al., 2017). After it comes to the surface and has been separated from the oil and gas, the produced water is generally injected in wells, either in non-hydrocarbon-bearing formations for disposal or in producing formations for further recovery, discharged in on-site evaporation or seepage pits, or reused by other sectors (McIntosh and Ferguson, 2019; Tiedeman et al., 2016; US Environmental Protection Agency, 2020).

Assessments of the quality of primary energy sources have traditionally been carried out by private companies and tend to focus on economic cost benefit analysis (CBA) and production efficiency (Giampietro et al., 2013). This specific focus on economic analysis reflects the interests and concerns of the energy industry in identifying promising investments in relation to their efforts of R&D. However, with the increasing public concern for the environment, interests are no longer restricted to the community of private investors. This broadened interest calls for a reconsideration of the set of criteria adopted in the analysis to complement the economic cost benefit analysis of the exploitation process with information relating to other relevant narratives, such as net energy supply, GHG emissions, freshwater requirements, disposal/reuse of oil produced water, and labor requirements. Indeed, an effective analysis has to also include the biophysical, environmental, and social costs and benefits that the exploitation of primary energy sources entails for society, without reducing the quantitative analysis to monetary variables.

In the 1980s, building on the idea of net energy analysis[1] (Maddox, 1978), Hall et al. (1981) proposed a heuristic rationale for assessing the quality of primary energy sources in relation to their usefulness for society under the name of Energy Return On Investment (EROI). The EROI concept is based on a biophysical narrative and hence represents an interesting alternative to CBA for assessing the performance of energy systems. It is a widely used approach, not only for fossil energy sources, but also for renewable energy sources (Cleveland, 2005; Cleveland et al., 1984; Cleveland and O'Connor, 2011; Court and Fizaine, 2017; Gagnon et al., 2009; Gever et al., 1991; Heun and de Wit, 2012; Kittner et al., 2016; Kubiszewski et al., 2010; Mansure and Blankenship, 2010). Nonetheless, despite attempts at standardization (Mulder and Hagens, 2008; Murphy et al., 2011), the EROI has seen important shortcomings in its implementation as a result of discrepancies in the definition of system boundaries (truncation problem) and in energy-quality adjustments, and in procedural/supply chain issues (energy-economy conversions – i.e. joint production dilemmas) (Giampietro et al., 2013; Hall et al., 2011). Indeed, the logic of net energy analysis becomes elusive when it is applied to specific operations (e.g., oil extraction) that form part of a larger and more complex network of transformations in which different types of costs and benefits as well as diverse policy considerations play a role.

In this paper, an alternative to the EROI is proposed to assess the biophysical performance of primary energy source exploitation. It builds on Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro et al., 2009), and is implemented with relational analysis. A historic data set on oil extraction in Ecuador is used to illustrate the approach. Relational analysis has been developed within the field of complex system analysis. It was first introduced in theoretical biology by Rashevsky (1954) and then further developed by Rosen (2012, 2005) within the field of category theory. Rosen's mathematical framework has been refined by Louie (Louie, 2017, 2013, 2009). Recently, relational analysis has been proposed as an analytical framework (variably referred to as MuSIASEM, relational analysis or MuSIASEM 2.0) to assess the resource nexus (Cabello et al., 2019; Serrano-Tovar et al., 2019) and to support quantitative story-telling around sustainability issues (Cadillo-Benalcazar et al., 2020a; Giampietro et al., 2020; Renner and Giampietro, 2020).

The specific goal of this paper is to demonstrate the usefulness of relational analysis for:

1. Providing a more robust biophysical assessment of the performance of oil extraction systems through the generation of benchmarks based on unitary metabolic processors for the various functional and structural elements of defined typologies of oil fields.
2. Broadening the assessment of the energy system by including the environmental implications (GHG emission, freshwater consumption, oil produced water disposal) of ageing conventional oil sources through diachronic (time series) and synchronic analysis (age structure).

The overall goal of the paper is to show that relational analysis is a promising approach for generating a more robust and richer information space for informing policies related to the clean energy transition and the environment.

The paper is organized as follows. In Section 2, the basic concepts of relational analysis are presented, using the illustrative case study from Ecuador. Section 3 illustrates the types of results that can be obtained with relational analysis including benchmark generation and diachronic and synchronic assessments of the performance of the oil extraction sector. The energy-water nexus is highlighted. Section 4 concludes and provides indications for further research.

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[1] The concept of net energy is derived from optimal foraging theory in ecology. According to this theory, organisms will adopt foraging strategies providing the maximum energetic return on the energetic investment.

2. Methodology: implementation of relational analysis to the extraction of oil

2.1. Basic concepts of relational analysis

In relational analysis, an energy system is considered as a metabolic network of structural (tangible) and functional (notional) elements. These elements are described by their expected profiles of inputs and outputs, i.e., their metabolic processors. Structural elements are combined together to express functional elements and different functional elements at a given level are combined into other functional elements at a higher level (see Figs. S1 and S2 in the supplementary material). For example, the structural elements 'oil fields' can be aggregated into three functional elements heavy, medium and light oil production. In turn, the latter functional units can be aggregated into a new functional unit of 'overall oil production'.

Relational analysis uses the four Aristotelean causes to identify the relevant structural and functional elements of the system and the expected relations among them (Giampietro, 2018; Giampietro and Renner, 2020; Renner et al., 2020b). Note that the term 'expected' refers to both the metabolic processors of the individual elements and the topological relations among them in the network. Information about the metabolic processors of the structural elements relates to the *formal cause*, that is, the blueprint of the technology (technical coefficients) of the individual structural elements. The availability of *material cause* characterizes the tangible aspect (the realization) of this process; i.e., the availability and the nature of the input and output flows and the funds used. The realization of the functions expressed by the various functional elements of the network refers to the *efficient cause*, i.e., how the system is expressing a given function (i.e., supplying oil). Finally, the combination of material, formal and efficient cause are justified by the existence of a *final cause* of the system, i.e., its purpose: why the system has been created in the first place (e.g., providing society with the required gasoline for transport).

The concepts of metabolic processor and grammar, developed within this logic, are key to the implementation of the quantitative analysis. The concept of metabolic processor is used to describe the characteristics of any individual structural (e.g., specific oil fields) or functional element (e.g., light oil supply) of the system in terms of an expected profile of inputs and outputs. The metabolic processor may be seen an extended biophysical production function. The concept of grammar, on the other hand, is used to describe the relations among the various structural and functional elements inside the system. Grammars relate the information referring to the formal and material cause (the metabolic characteristics of structural elements operating at the local scale) to the information referring to the efficient cause (the metabolic characteristics of an integrated set of processes observed when combining lower-level structural elements into a functional unit) (Giampietro, 2018). Further details on the application of the theory of relational analysis are available in (Giampietro, 2018; Giampietro and Renner, 2020; Renner et al., 2020b) and summarized in Sections 1 and 2 of the supplementary material.

2.2. Definition of the metabolic processor

The definition of the metabolic processor is a key step and involves the selection of the various inputs and outputs considered in the analysis. In the illustrative case study of Ecuador, it focuses on the links among different types of attributes in four distinct spheres of analysis relevant for policymaking in relation to oil extraction (see Fig. 1). These four attributes/spheres are:

1. The characteristics of the primary energy source exploited (sphere A). In the case of crude oil, factors such as viscosity, location and depth of the stock, and the relative amount of formation water affect the performance of the exploitation process and must be taken into account (associated with the identity of the metabolic processor) to study potential future changes. The age of the well is another impor-

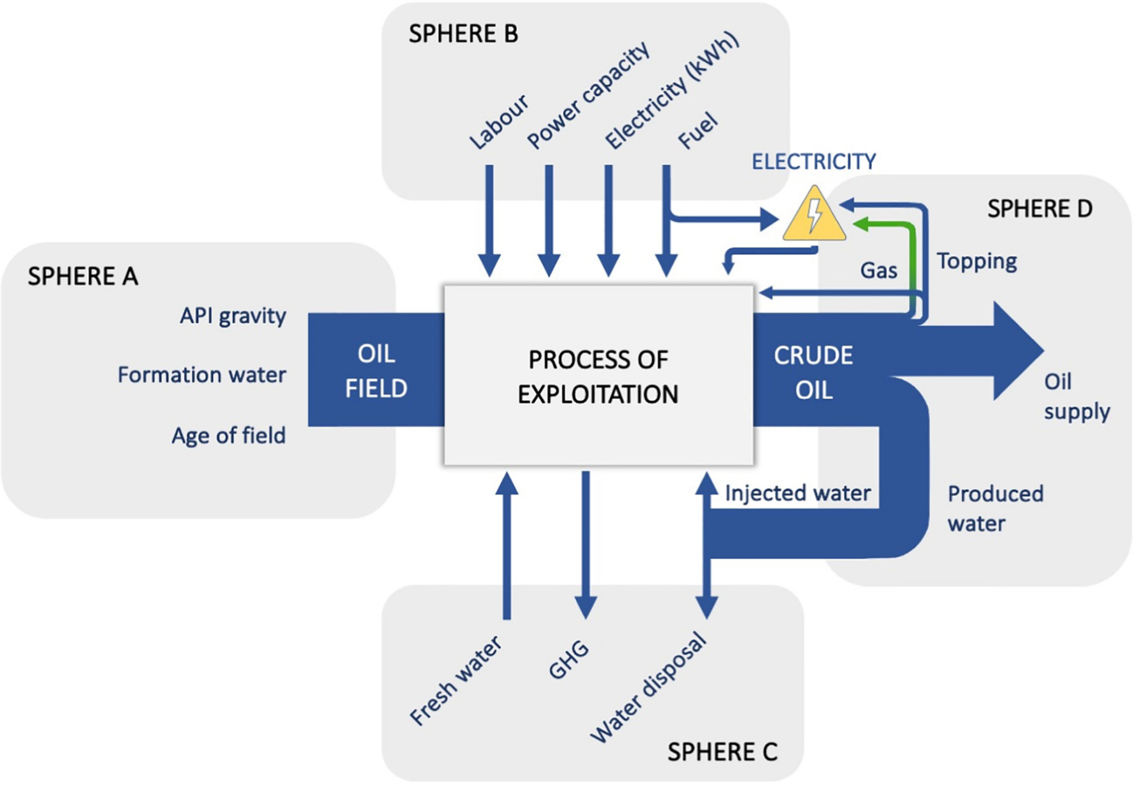


Fig. 1. The metabolic processor for conventional oil exploitation in Ecuador.

tant factor. Primary energy sources are derived from the biosphere (generated by processes beyond human control) and their characteristics determine the FEASIBILITY of the exploitation on the supply side (potential external limits).

2. The profile of external inputs required from the technosphere for the exploitation process (sphere B). This includes the level of power capacity of the selected technology of extraction, labor input, and external inputs of electricity and fuels (not obtained from the internal loop of exploitation). These inputs are recorded and processed separately (i.e., they are not aggregated using monetary values or energy quality indices). They provide information that is relevant for studying the VIABILITY of the system (the economic and technical constraints associated with processes under human control). Note that in the Ecuador case, until September 2017, external electricity from the grid was not used, all electricity was generated on-site. Since September 2017, it represents less than 5% of the total electricity consumed in the extraction system (CELEC, 2017). External fuels in the Ecuador case are predominantly diesel and gasoline.
3. The inputs and outputs exchanged with the natural environment (biosphere) in the exploitation process (sphere C). These include consumption of fresh water and generation of greenhouse gases (GHGs) and oil produced water. In the case of Ecuador, freshwater consumption concerns predominantly local river water. GHG emission concerns the on-site emission from production flaring (to dispose of the unwanted petroleum gas) and from the on-site use of fuel for heavy machinery and generation of electricity. Produced water is defined here as: "the water (brine) brought up from the hydrocarbon-bearing strata during the extraction of oil and gas, and can include formation water, injection water, and any chemicals added downhole or during the oil/water separation process" (US Environmental Protection Agency, 2020). In this case study of Ecuador, produced water basically concerns formation water as secondary and tertiary oil recovery (water and steam flooding) are not practiced on a significant scale. Inputs and outputs in this sphere relate to the environmental pressures associated with the exploitation process, which can impact the embedding ecosystems, and are relevant for studying the FEASIBILITY of the process on both the supply (freshwater requirement) and sink side (GHG emission, disposal of produced water).
4. The internal loops of energy and water within the exploitation process (sphere D). This refers to (i) the fraction of the oil output that is used directly for energy generation in the exploitation process through the use of 'topping' units, (ii) the gaseous hydrocarbons produced that are used for electricity generation, (iii) the fraction of the produced water that is re-injected for enhanced oil recovery. This sphere of analysis deals with the technical aspects of the exploitation process. Note that in the Ecuador case, the internal loop of water is negligible. Virtually all the produced water is disposed of in the environment (sphere C).

Further details on the construction of the processors are provided in Section 1 of the supplementary material.

2.3. Definition of grammars

Grammars define the expected relations among the structural and functional elements inside the metabolic network associated with the operations of the energy system under analysis. In the present study, the structural (tangible) elements are represented by the specific oil fields (i.e., the lowest level at which observations are made). The definition of the functional elements is obtained at a higher level of analysis and can be either *notional*, if obtained from the metabolic characteristics of the composing structural elements (bottom-up representation), or 'observed' if based on the use of (aggregate) statistics describing the functional unit at its own level (top-down representation). Neither the notional nor the 'observed' representation of a functional element is based on direct measurements of tangible entities, but determined by, respectively, the analyst's and statistician's choice of how to combine structural units into a functional unit. Indeed, it is possible to define different functional elements at any given hierarchical level of analysis depending on the logic of the aggregation of lower-level elements. This logic, in turn, will depend on the purpose of the study.

Relevant attributes for the definition of functional elements in the present study are typology of oil extracted (light, medium, heavy), age of the oil field (years of operation), and geographic location of the oil field. The different aggregations of the characteristics of metabolic processors across hierarchical levels of analysis according to the different criteria used in the current study are shown in Sections 1 and 2 of the supplementary material.

2.4. Data sources

The oil extraction system in Ecuador is organized over three (hierarchical) geographic levels (see Fig. S5 in the supplementary data file), in line with its Hydrocarbons Law ("Ley de Hidrocarburos") of 1978, last modified 21 May 2018 (Ministerio de Energía y Recursos Naturales no Renovables, 2018), which regulates the Ecuadorian oil and gas industry. Fields ("campos") are the smallest units (structural elements) for the exploration and exploitation of hydrocarbon deposits; 178 fields in total were analyzed (level *n*-3). Blocks ("bloques") are areas of no more than 200 thousand hectares that contain various oil fields; there are 36 blocks in total (level *n*-2). Prospects ("tren prospective") are geographical areas with similar geological characteristics with hydrocarbon potential that cover various blocks and fields; 6 prospects were considered in line with studies of Ecuador's Ministry of Energy and Non-Renewable Natural Resources (MERNNR, 2018) (level *n*-1). The national level is defined as level *n*. The analysis covers all of the 178 oil fields of Ecuador active during (some part of) the period 1972 to 2018 (thus covering total national oil production). Production from natural gas fields was not considered.

Data on the quantity of produced water are not readily available in Ecuador. For this reason, produced water was approximated from the basic sediment and water content (BSW) of the crude oil extracted, measured at the wellhead. BSW (also referred to as 'water cut') corresponds to the content of free water and sediments in the crude oil extracted, and is expressed as a percentage of the total volume of crude oil extracted (%). The BSW, *if measured at the wellhead*, can provide a fair measure of the oil-produced water volume (m^3) of the extraction system. It will slightly overestimate the produced water because besides water, BSW also includes sediments, and not all of the water may be removed from the oil in the on-site separation process. The latter factor is irrelevant in this case, as in Ecuador, by law, BSW content of the extracted crude oil must be reduced to <1% before transport (Ministerio de Energía y Recursos Naturales no Renovables, 2004). Hence, for the purpose of this study, BSW content of the crude oil extracted does provide a sufficiently reliable estimate of the produced water to compare the performance of the extraction process in space and time.

Current and historical data on oil production, oil quality (API gravity) and basic sediment and water content (BSW) for the individual oil fields (structural elements, level *n*-3) was obtained from databases, reports and field information from various public institutions (Agencia de Regulación y Control Hidrocarburífero – ARCH; Ministerio de Energía y Recursos Naturales no Renovables – MERNNR, previously Ministerio Coordinador de Sectores Estratégicos – MICSE) and public and private companies in the energy sector of Ecuador (ARCH, 2020; Petroamazonas, 2020; Secretaría de Hidrocarburos, 2018). Oil production (or oil supply) refers to the oil obtained from the crude oil extracted, after separation of gaseous hydrocarbons and produced water. The total volume of crude oil extracted (the system size) is approximated as the sum of the volume of oil supply obtained and the estimated volume of produced water. Values reported are yearly averages.

Furthermore, for each oil field, data on the inputs and outputs characterizing the exploitation process (shown in the graphical abstract) were collected. Data on electricity, fuel, and power capacity were obtained from the statistics of (ARCH, 2020; ARCONEL, 2018; Petroamazonas, 2020; SISDAT, 2019); data on labor input from (INEC, 2019), and fresh water consumption from (Parra et al., 2018). GHG emission of oil exploitation was estimated from gas flaring and the on-site use of fuel for machinery and electricity generation, using data from (ARCH, 2020; Petroamazonas, 2020). However, not for all oil fields historical information could be obtained for all the inputs and outputs of the processor and, therefore, it was necessary to elaborate the information collected at the level of oil fields (*n*-3) by using benchmarks and triangulating with data from statistics at higher levels of observation (see Section 3.2).

2.5. The relation between the volume of crude oil extracted, BSW and oil supply

Note that the percentage of BSW is measured at the wellhead and hence assessed in relation to the volume of crude oil *extracted*. The volume of crude oil extracted represents the volume of the exploitation system to which the various inputs and outputs relate. Nonetheless, all the unitary processors in this study are expressed in relation to the oil supply (output) to society. The difference between the volume of oil extracted and the volume of oil supply is the volume of oil produced water and sediments that are separated from the crude oil on-site.

The reason for expressing the unitary processors in relation to the oil supply is two-fold: first, because oil supply is the main parameter of interest; second, because most of the statistics/benchmarks available are provided per unit of oil supply.

The relation between the volume of crude oil extracted (V), BSW (as a *percentage* of the crude oil extracted), and the volume of oil supply (S) is as follows:

$$S = V \times \left(\frac{100 - \mathrm{BSW}}{100}\right)$$

Hence, to convert the inputs and outputs of a given unitary processor expressed per unit (m^3) of oil supply to inputs/outputs per unit (m^3) of crude oil extracted, they must be multiplied with (100 − *BSW*)/100] using the BSW value (%) of the structural or functional element in question.

3. Results

3.1. Overall description of the oil extraction system of the Ecuador case

Oil extraction in Ecuador began in 1911 with the operation of the fields in the Costa Region. However, the oil boom only started in 1972 with the development of the oil fields in Amazonia. Since 1972, Ecuador's oil production has been growing significantly (Fig. 2). In 1987, the Trans-Ecuadorian Pipeline System (SOTE), the only pipeline up to that date, suffered a rupture, as a result of two earthquakes, that forced oil production to temporarily stop in several fields in the Amazon. In November 2003, the Heavy Crude Pipeline (OCP) came into operation, which allowed national oil production to increase to 31 million m^3 in 2006 (see Fig. 2). Between 2007 and 2016, several changes took place in Ecuador's hydrocarbon policy, the institutional framework was restructured, the hydrocarbon law was reformed, the modality of oil upstream contracts was changed, and several fields were transferred to public companies (Martínez et al., 2016), all of which influenced national oil production. At the end of this period, a maximum annual peak of 32 million m^3 of oil was reached (Fig. 2). Since then, national production has fallen as a result of the natural decline in productivity of the reservoirs. This decline has been temporarily offset by the entry into operation of new fields at the end of 2016, such as Tiputini and Tambocha. As of March 2020, the production from these new fields accounted for approximately 20% of the national production (ARCH, 2020).

As illustrated in Fig. 3, the BSW content of the raw crude oil extracted and the quality of the oil produced dramatically changed in time. In 1972, with only 6 active fields, national oil production (total at national level) stood at 4.5 million m^3, of which 92% medium oil and 8% light oil. The average BSW content of crude oil in that year was marginal at 4% and the total volume of crude oil extracted (system size) was 4.7 million m^3. In 2018, 29.9 million m^3 of oil were produced, of which 52% corresponded to medium oil and 48% to heavy oil. Average BSW content of the crude oil increased to no less than 87%, corresponding to a total volume of crude oil extracted in 2018 of 230 million m^3. The environmental implications of this development are substantial.

The data in Fig. 3 confirm the progressive depletion of high-quality oil reserves in Ecuador and the increase in extraction of lower quality oil (heavy oil) and the concomitant increase in produced water and enlargement of the system size (total volume of crude extracted). Nonetheless, oil being the most important export in the country, the Ecuadorian government plans to further increase

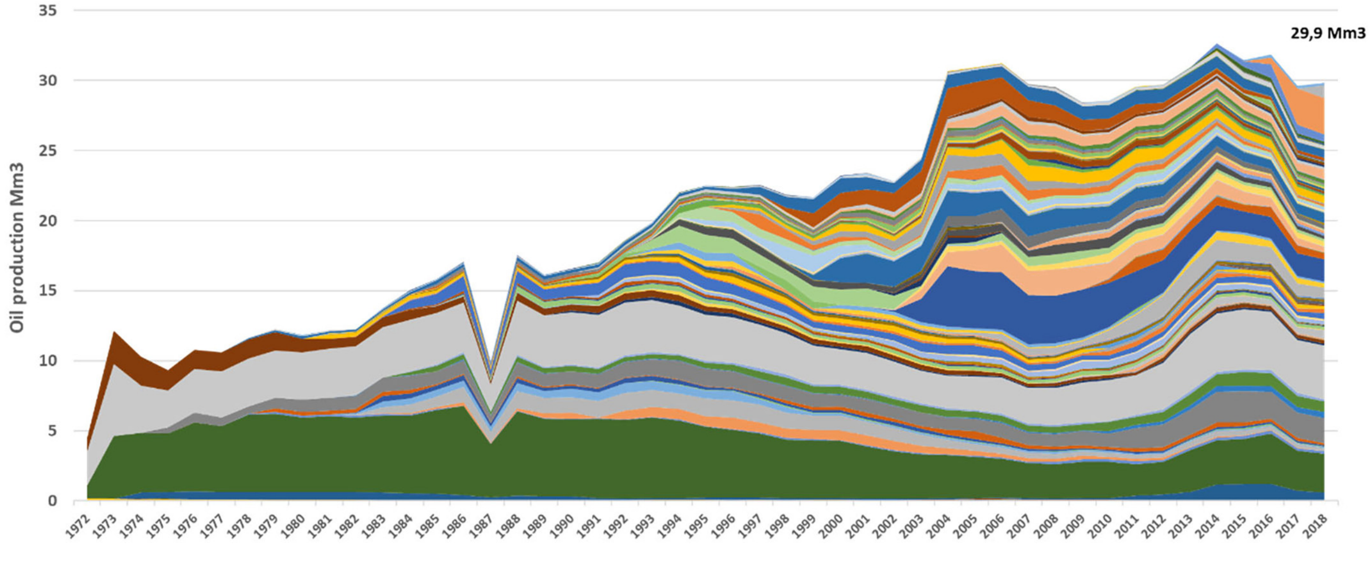


Fig. 2. Evolution in the exploitation of oil fields in Ecuador over the period 1972–2018. Oil production volume refers to the oil supply obtained from the raw crude oil extracted, after separation of produced water, sediments and gaseous hydrocarbons.

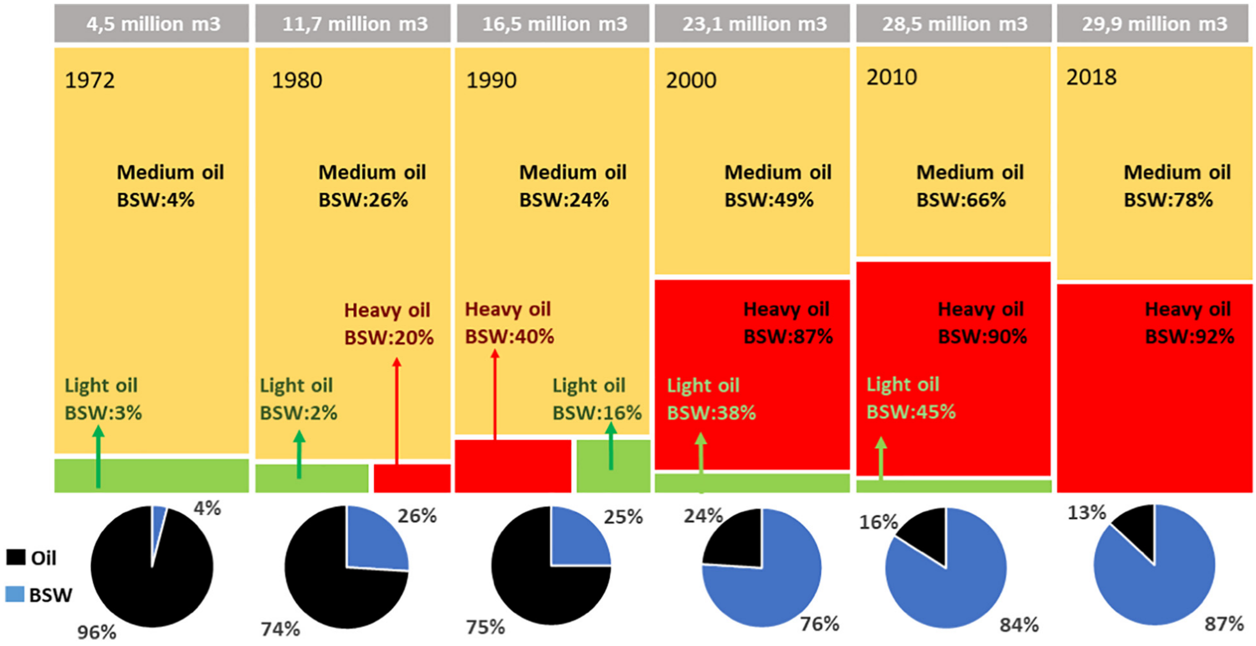


Fig. 3. Changes in the characteristics of the crude oil extracted in Ecuador in the period 1972–2018. Pie graphs at the bottom represent the relative content (% v/v) of oil (in black) and BSW (in blue) of the total volume of crude oil extracted. Bar graphs show the relative share of light (red), medium (yellow) and heavy oil (green) in % v/v. BSW content (% v/v) of the different oil qualities is also shown. Total volume of the oil supplied (after separation of produced water and gaseous hydrocarbons) is shown in grey at the top of the bar graphs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

its production up to 700,000 barrels (111×10^3 m^3) per day (equivalent to 40 million m^3 per year) by 2021 (EFE, 2017).

3.2. Benchmarks and typologies of relations

In relational analysis, the triangulation of information across different data sources generates redundancy in the information space that allows the inference of missing data and reduces the uncertainty associated with the quantitative representation. In particular, benchmarks (notional representations of unitary metabolic processors) can be used to fill gaps in and cross-check the data set, to characterize typologies of structural and functional elements, and to anticipate future changes (scenario analysis). In this section, we illustrate the use of benchmarks to define oil field typologies and fill data gaps in the metabolic processors of the structural elements (inputs/outputs). Indeed, historical data sets could not be obtained for all oil fields in relation to all the input and output flows. Nonetheless, complete time series were available for all oil fields with regard to the oil supply obtained, API quality, and the BSW content of the crude oil extracted. These data were instrumental for the generation of benchmarks for the structural elements. More details on the uncertainty and error propagation in relational analysis are provided in Section 2 of the supplementary material.

Benchmarks (reference to unitary metabolic processors) were generated for typologies of oil fields, classified by API, BSW content and age, using the available data on the inputs and outputs of the metabolic processors of individual oil fields. To this purpose, standard API gravity classification was adapted and expanded to 6 categories to obtain more accurate benchmarks (see Fig. 4). As shown in Fig. 4, BSW content of the crude oil extracted is dependent on the API quality, and, for each quality, steadily increases as the oil field ages. The graphs in Fig. 4 are based on time series for all oil fields in operation during the period 1972–2018, 178 fields in total, including those exhausted (and abandoned) or taken into production during this time interval. Equations for expected BSW content of crude oil extracted as a function of oil field age for the 6 API oil field typologies distinguished are also shown in Fig. 4.

The BSW versus age curves shown in Fig. 4 were used to generate the computational structures defining how the profiles of individual inputs and outputs of the metabolic processors of the structural elements change with ageing (see Section 3 of the supplementary material for the computational structures). In this way, data gaps were filled for the oil fields with incomplete historic records (missing data for the profile of inputs and outputs of their processors for specific years). In addition to filling the data gaps, this approach has also been used to describe the typologies (notional representations) of oil fields. It also permits to anticipate changes in the future performance of active oil fields (not shown in this paper).

Having defined the metabolic characteristics of the structural types (fields)—in relation to type of oil and age—diachronic, synchronic and multi-criteria analyses were performed. Examples of the types of results obtained are illustrated in the next sections.

3.3. Diachronic view at a given level

A diachronic view of the system provides indications about changes in the performance of the oil exploitation system (defined at a given level of observation) over a certain time window at a specific hierarchical level of analysis. An example of this type of characterization is given in Fig. 5. It shows that as the system ages, it requires more inputs per unit of oil production (national level) and creates more pressure on the environment in terms of GHG emission and produced water. The analysis also shows that this phenomenon is created by the decrease in the quality of oil (API) with time (i.e., with time the better fields become exhausted and are eventually abandoned; the new fields taken into production are of poorer quality) and the increase in water cut of the crude oil (BSW) with increasing time of exploitation.

In particular, in 1975, hardly any heavy oil was extracted and BSW content averaged only 18% at the national level (Fig. 5). For each cubic meter of oil extracted, the system consumed 66 kWh of electricity (generated on-site), 0.126 GJ of fuel (internal loop plus external fuel for use as such), 1.72 h of labor and 0.137 m^3 of fresh water, and generated 0.22 m^3 of produced water and 0.073 metric ton of GHG. In 2018, as much as 40% of the crude extracted was classified as heavy oil and the

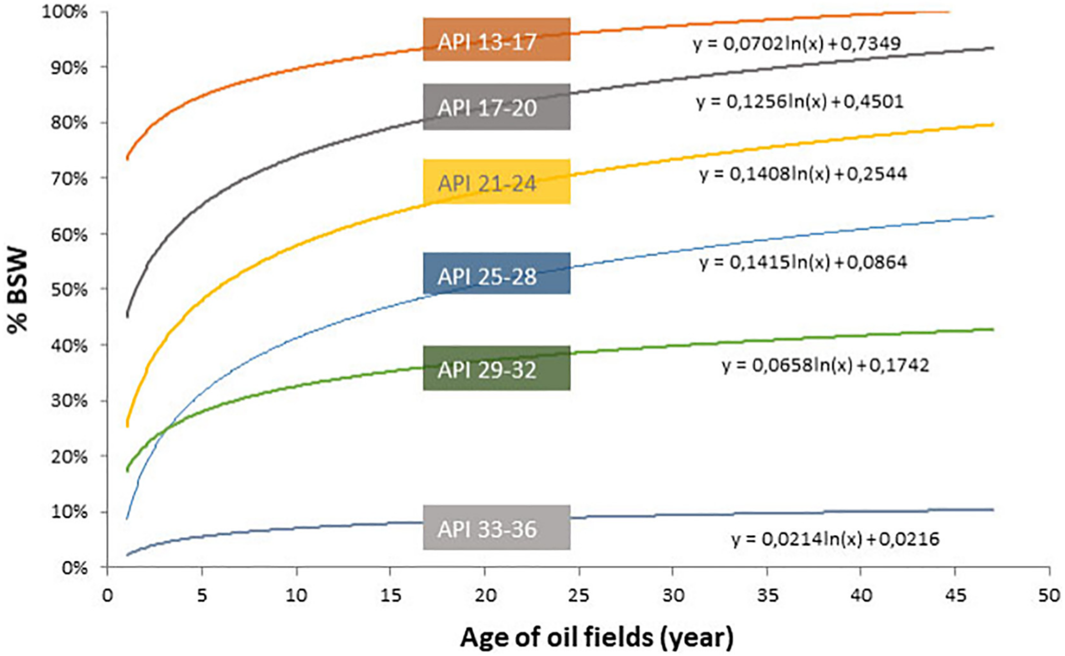
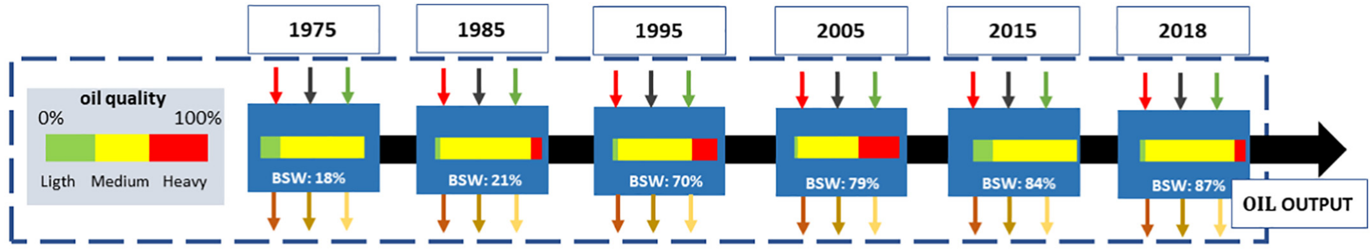


Fig. 4. Increase in BSW content of the crude oil extracted (y-axis) with the ageing of oil fields (x-axis) for each API category of crude oil extracted. Data are based on the 178 oil fields in Ecuador over the period 1972 to 2018. Standard API classification was adapted (see text). Equations for expected BSW (y) as a function of age (x) for each API category are also shown.

BSW content at national level was 87%. The extraction of 1 m^3 of oil required 164 kWh of electricity (+147%), 0.178 GJ of fuel (+41%), 2.7 h of labor (+62%) and 0.2 m^3 of fresh water (+48%), and generated 6.7 m^3 of produced water (+ 2911%) and 0.22 t of GHG (+203%). In absolute amounts (extensive flows), GHG emission from oil extraction increased from 682 × 10^3 tons in 1975 to 6633 × 10^3 tons in 2018, and the amount of produced water increased from 2.1 × 10^6 m^3 in 1975 to 201 × 10^6 m^3 in 2018. Fresh water consumption levels (water to oil ratio in *v*/v) observed in Ecuador are typical for primary oil recovery (Tiedeman et al., 2016). Where secondary (and tertiary) recovery is practiced, values will be significantly higher (Tiedeman et al., 2016)

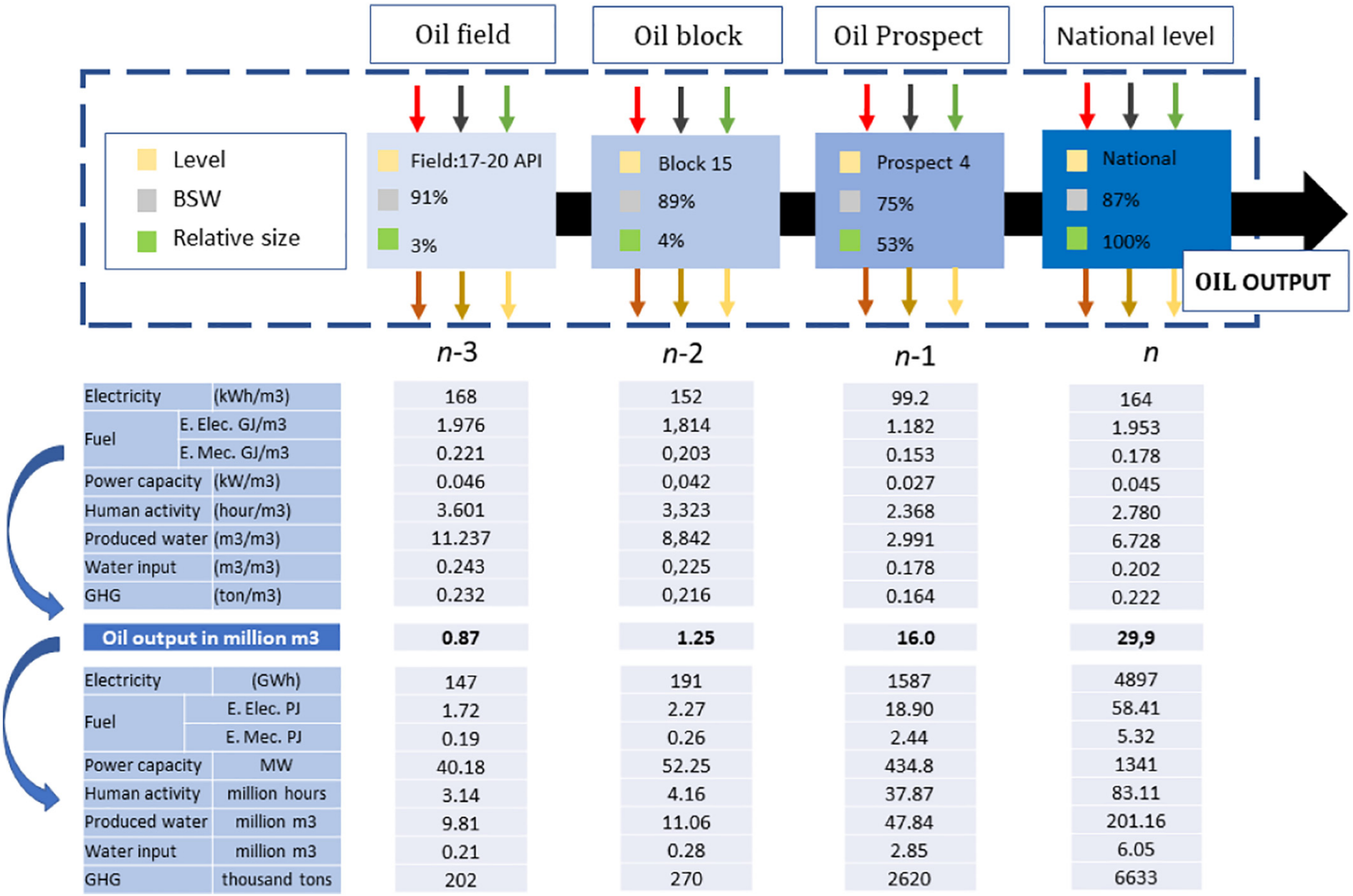
3.4. Multilevel synchronic view

On the other hand, a *synchronic* view of the system provides indications about the differences in the performance of the oil exploitation



		1975	1985	1995	2005	2015	2018
Electricity	(kWh/m3)	66.2	70.9	96.2	143.4	123.6	163.8
Fuel	E. Elec. GJ/m3	0.786	0.843	1.145	1.711	1.477	1.953
	E. Mec. GJ/m3	0.126	0.136	0.154	0.178	0.165	0.178
Power capacity	(kW/m3)	0.018	0.019	0.026	0.039	0.034	0.045
Human activity	(hour/m3)	1.721	1.873	2.262	2.739	2.579	2.780
Produced water	(m3/m3)	0.223	0.259	2.323	3.783	5.385	6.728
Water input	(m3/m3)	0.137	0.146	0.168	0.196	0.188	0.202
GHG	(Ton/m3)	0.073	0.086	0.122	0.191	0.182	0.222
Oil output in million m3		**9.3**	**15.8**	**22.4**	**30.9**	**31.5**	**29.9**
Electricity	(GWh)	616	1120	2163	4430	3890	4897
Fuel	E. Elec. PJ	7	13	26	53	46	58
	E. Mec. PJ	1.1	2	3	5	5	5
Power capacity	MW	169	307	593	1214	1066	1342
Human activity	million hours	16	29.6	50.9	84.6	81.2	83.1
Produced water	million m3	2.1	4.1	52.3	116.9	169.5	201.2
Water input	million m3	1.27	2.31	3.77	6.05	5.92	6.05
GHG	thousand Ton	682	1357	2735	5913	5738	6633

Fig. 5. Diachronic view of the metabolism of oil extraction at national level for the period 1975–2018. Electricity (first row) represents electricity generated on-site from fuel; fuel represents external and internal fuel (including gaseous hydrocarbons produced) which is either destined for the on-site generation of electricity (E. Electric) or used as such in machinery (E. Mechanic).



		n-3	n-2	n-1	n
Electricity	(kWh/m3)	168	152	99.2	164
Fuel	E. Elec. GJ/m3	1.976	1,814	1.182	1.953
	E. Mec. GJ/m3	0.221	0,203	0.153	0.178
Power capacity	(kW/m3)	0.046	0,042	0.027	0.045
Human activity	(hour/m3)	3.601	3,323	2.368	2.780
Produced water	(m3/m3)	11.237	8,842	2.991	6.728
Water input	(m3/m3)	0.243	0,225	0.178	0.202
GHG	(ton/m3)	0.232	0,216	0.164	0.222
Oil output in million m3		**0.87**	**1.25**	**16.0**	**29,9**
Electricity	(GWh)	147	191	1587	4897
Fuel	E. Elec. PJ	1.72	2.27	18.90	58.41
	E. Mec. PJ	0.19	0.26	2.44	5.32
Power capacity	MW	40.18	52.25	434.8	1341
Human activity	million hours	3.14	4.16	37.87	83.11
Produced water	million m3	9.81	11.06	47.84	201.16
Water input	million m3	0.21	0.28	2.85	6.05
GHG	thousand tons	202	270	2620	6633

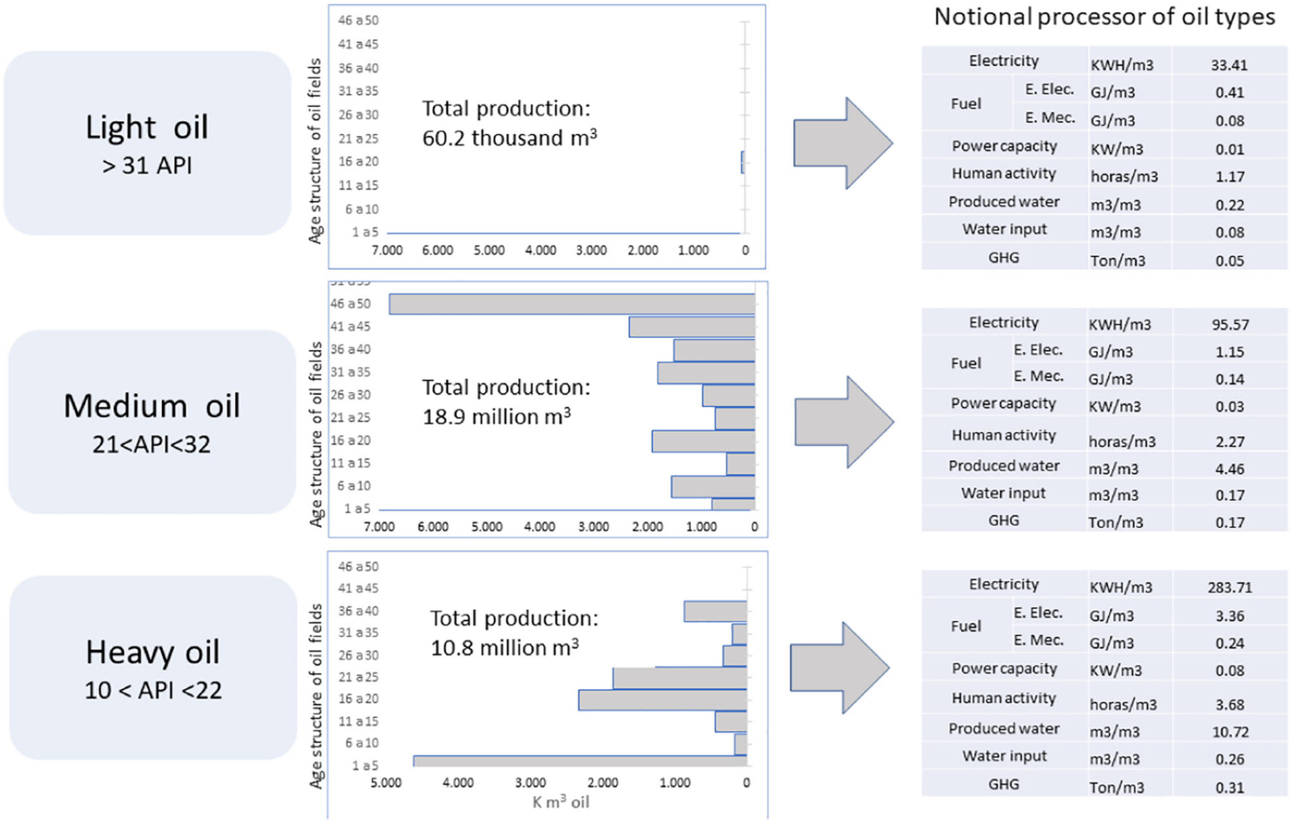
Fig. 6. Multilevel synchronic view across geographic scales of the metabolic network. Data refer to 2018. Electricity (first row) represents the electricity generated on-site from fuel (no external electricity is used in Ecuador); fuel represents external and internal fuel (including gaseous hydrocarbons produced) which is either destined for the on-site generation of electricity (E. Electric) or used as such in machinery (E. Mechanic).

system when observed simultaneously across different levels of observation at a specific point in time. The characterization of the oil extraction sector of Ecuador at different geographic scales of analysis—i.e. oil field, oil block, oil prospect, national aggregate—is illustrated in Fig. 6 at a given point in time (2018). Results were obtained through the functional aggregation procedure detailed in Section 1 of the supplementary material and the grammar shown in Fig. S5 of the supplementary material. This synchronous analysis shows some possible representations of different benchmarks (inputs and outputs per unit of oil production) at different levels of analysis. Depending on the hierarchical level of assessment, different input/output benchmarks are found. For instance, in this specific example, the block observed at level *n*-2 requires 152 kWh of electricity per m^3 of oil production, whereas its corresponding prospect requires 99 kWh per m^3 of oil production and the oil sector as a whole (level *n*) 164 kWh per m^3 of oil. The situation is reversed for labor: 3.3 h per m^3 of oil production are required in the observed block versus 2.4 and 2.8 h per m^3 of oil production at the prospect and national level, respectively. Marked differences are seen in the estimated amount of produced water: 11,2 m^3 water per m^3 of oil production at the field level, 8.8 m^3/m^3 at the level of the block, and 3.0 and 6.7 m^3 per m^3 of oil production at the prospect and national level, respectively. GHG levels are not markedly different among the hierarchical levels.

The characterization of the age structure of the oil extraction sector of Ecuador by oil typology (API classification: light, medium, heavy) is shown in Fig. 7. This figure shows that fields recently taken into production (1–5 years old) are predominantly of lesser quality (heavy oil) (see bottom graph in particular). It also shows that the age structure of the population of oil fields is reflected in the overall characteristics (different profile of inputs and outputs) of the functional processors of API oil quality defined in notional terms at a higher hierarchical level (right-hand column in Fig. 7). Despite the oil fields being younger, the exploitation of heavy oil (notably in prospect 6, see Table S1 of the supplementary data) generates more pressure on the environment than that of medium and light oil.

The different oil prospects also exhibit different age structures (see Table S1, supplementary data file), which has important implications for their expected future performance. For instance, prospect #4, with an oil supply of 15×10^6 m^3, represented half of the total national production in 2018. Three quarters of this production concerns fields producing relatively good quality medium oil, the remaining quarter concerns heavy oil. However, two thirds of the production of this medium oil in prospect #4 is derived from fields in the age range of 36–50 years. This has important implications for the future.

The policy relevance of the organization of the quantitative analysis in this way is obvious. The option to disaggregate the analysis not only in relation to API typologies of oils and age class, but at the same time also in relation to geographic area, allows the analyst to relate the environmental supply requirements (crude availability and quality as well as fresh water requirements) and sink requirements (capacity of absorbing produced water and the pollutants it contains as well as GHG emissions) to the local characteristics of the natural processes expected to provide the supply and sink capacity. This is particularly relevant in this illustrative case study, given that most of the oil extraction in Ecuador takes place in the Amazon basin in the northeast of the country (expect for prospect 1, which is located in the coast area), home to large areas of tropical rain forest located at the headwaters of the Amazon River network and home to several groups of indigenous people. Prospects 5



Notional processor of oil types

Electricity		KWH/m3	33.41
Fuel	E. Elec.	GJ/m3	0.41
	E. Mec.	GJ/m3	0.08
Power capacity		KW/m3	0.01
Human activity		horas/m3	1.17
Produced water		m3/m3	0.22
Water input		m3/m3	0.08
GHG		Ton/m3	0.05

Electricity		KWH/m3	95.57
Fuel	E. Elec.	GJ/m3	1.15
	E. Mec.	GJ/m3	0.14
Power capacity		KW/m3	0.03
Human activity		horas/m3	2.27
Produced water		m3/m3	4.46
Water input		m3/m3	0.17
GHG		Ton/m3	0.17

Electricity		KWH/m3	283.71
Fuel	E. Elec.	GJ/m3	3.36
	E. Mec.	GJ/m3	0.24
Power capacity		KW/m3	0.08
Human activity		horas/m3	3.68
Produced water		m3/m3	10.72
Water input		m3/m3	0.26
GHG		Ton/m3	0.31

Fig. 7. Age structure of oil fields by extracted oil quality (API: light, medium, and heavy). Data refer to 2018. Age category refers to the number of years the oil field has been in production. Inputs and outputs shown (right hand column) are expressed on a unitary basis (per m^3 of oil supply).

and 6 in particular cross the more sensitive areas and some of their fields and blocks are close to or within the Yasuni reserve (Finer et al., 2010).

3.5. Multi-criteria analysis of the performance of field oils

The performance of oil fields, oil blocks, oil prospects and the whole oil sector depends on several distinct intrinsic and extrinsic factors. Single or composite indices of performance, such as provided by CBA, are necessarily based on the hegemonization of one relevant narrative/criteria over others (Checkland and Scholes, 1990; Saltelli and Giampietro, 2017). A flexible accounting method such as relational analysis can provide a solution by providing a holistic characterization of the performance of the system in the form of a set of interconnected criteria relevant for informing decision making, i.e., a multi-criteria characterization (Greco et al., 2016; Nijkamp et al., 1990). Multi-criteria characterizations do not collapse the rich information space into a composite indicator, but show how the indicators are linked within the given option space (e.g., through a radar or spider diagram). Obviously, to inform policy, it is essential that the choice of the criteria and indicators is made in collaboration with decision-makers and other social actors affected by the decisions (Munda, 2010).

A simplified example of a multi-criteria characterization of the performance of the Ecuadorian oil sector is shown in Fig. 8. Other attributes can be considered by adding other relevant input and output flows to the relational analysis.

The example shown in Fig. 8 covers four different types of criteria: (i) environmental pressure (the selected indicators are GHG emission and the produced water disposed of in reservoir sinks); (ii) social effects (the selected indicator is the labor requirement, which is related to employment); (iii) technical coefficients (the selected indicator is total electricity consumption (external plus internal)); (iv) economic performance (the selected indicator is: the profit generated in the operation). In this simplified illustrative example, profit is roughly estimated from the oil price (55 USD/barrel) versus the costs associated with energy consumption and labor. Other expenses were not considered. Labor cost was estimated at 6USD/h; electricity cost at 0.25 USD/kWh and fuel cost at 70 USD/barrel of diesel.

The example shown in Fig. 8 confirms that oil fields that yield crude oil with a lower water cut (X2, X3 and X5), require less electricity and labor and therefore create less pressure on the environment in terms of GHG emission and water disposal and generate more profit. The amount of produced water, in turn, depends on the quality of the oil, the age of the field and the location (geographic formation) (see Fig. 7 and Table S1). While fields X2, X3 and X5—those with the higher economic profit—produce crude with an API of, respectively, 26, 21 and 17, the other two fields shown (X1 and X4) produce oil of lower quality (both API 15) and have a lower profit.

In practical applications the set of selected indicators should be organized in radar/spider diagrams, in which targets can be added to visualize the performance in relation to the various indicators in order to facilitate the process of decision-making (Nijkamp and Ouwersloot, 1997).

4. Discussion and conclusions

4.1. Novelty, added value and shortcomings of relational analysis

In this paper, a novel approach based on relational analysis has been put forward to analyze the biophysical performance of the exploitation of conventional oil sources. This approach is novel in that it recognizes and respects the complexity of the system under study. Relational analysis generates a diversified information space that keeps semantic coherence across different descriptive domains, i.e. different dimensions and levels of analysis. It highlights the *relations* among the structural and functional elements of the system. In comparison to CBA and EROI, relational analysis offers the advantage of linking the various

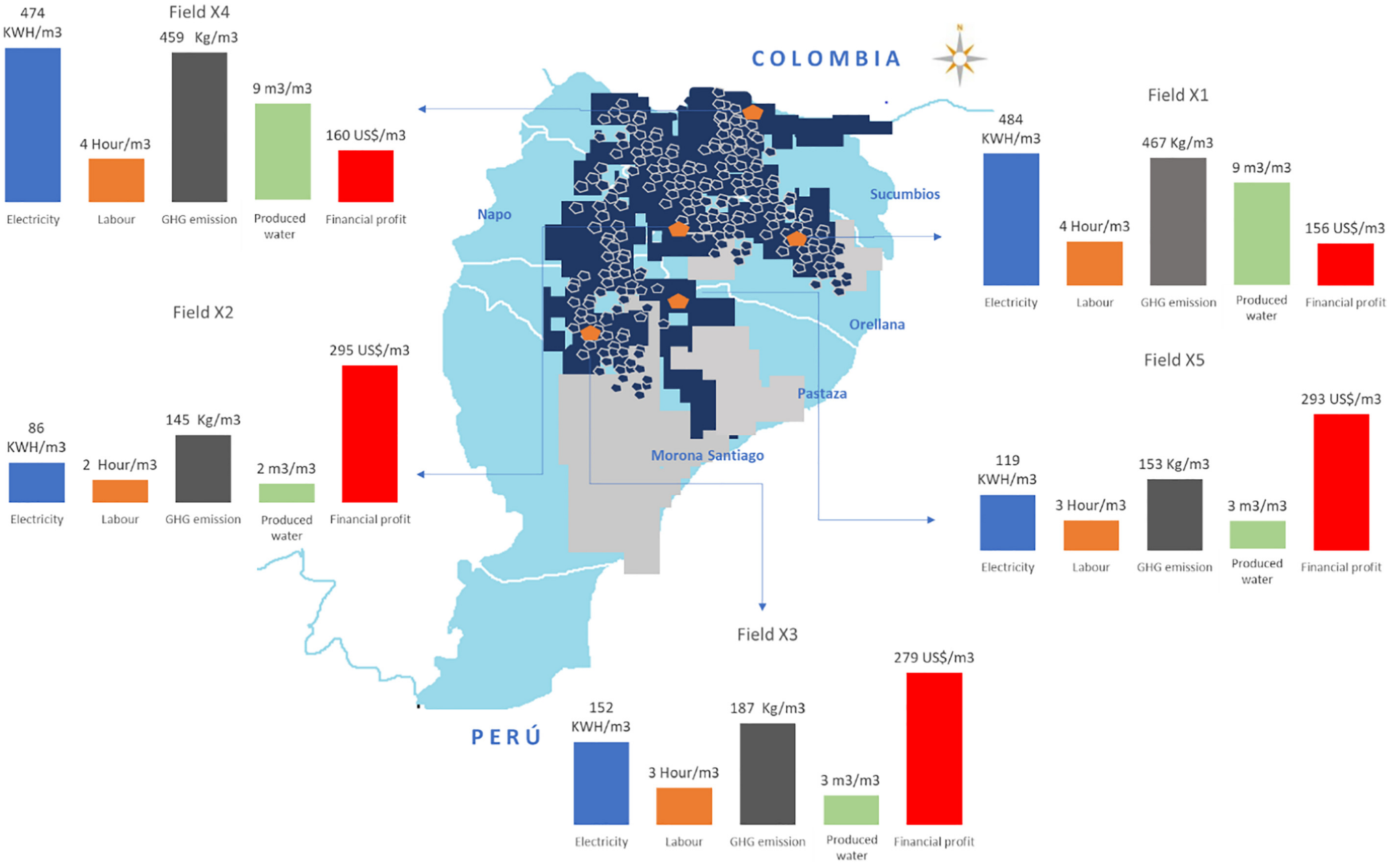


Fig. 8. A multi-criteria visualization of the oil exploitation process in Ecuador.

elements of the resource nexus into a representation based on metabolic processors without using simplification methods that reduce all the inputs and outputs into a single metric (e.g., monetary value in CBA or energy equivalent in EROI). The approach is semantically open and therefore not limited to the field of energy, but applicable to a broad range of environmental issues at different hierarchical levels (e.g., agriculture/food security in the EU, see (Cadillo-Benalcazar et al., 2020b; Renner et al., 2020a)). In this particular illustrative case study, the simultaneous use of different metrics for assessing the flows of energy carriers of different quality and the flows of water entering and exiting the process as well as the inclusion of required fund elements (labor and power capacity) allows the analyst to highlight the energy-water nexus and track relevant characteristics of the energy exploitation process in relation to both its socio-economic (e.g., employment) and ecological dimension. It can contextualize the assessment in relation to various policy-relevant issues: (i) the overall performance of the system (e.g., relevance of oil supply for export); (ii) the specific performance of geographic areas (e.g., relevant for the analysis of environmental impacts in sensitive areas, such as the Amazon basin in Ecuador); (iii) the functional performance of specific combinations of processes; and (iv) the state of the art of technologies used to carry out specific local processes at the level of structural types (e.g., potential introduction of secondary recovery).

As mentioned, relational analysis not only produces diverse "quantitative results", but also identifies the pattern of relations that generated these results. This facilitates the identification of the factors that determine the weakness/robustness of the results. Relations among structural and functional elements are complex in that they admit many-to-one mappings (Giampietro and Renner, 2020). This permits the coexistence of non-equivalent representations of the same system (bottom-up versus top-down) and generates redundancy in the information space. This redundancy allows the analyst to improve the robustness of the quantitative characterization through a triangulation over different data sources. This avoids the propagation of errors, and as shown in this study, solves the problem of missing data.

The present study illustrates that for complex metabolic systems the outcome of any quantification process is determined by the pre-analytical choices of the analyst (choice of structural/functional elements, inputs/outputs of the metabolic processor, choice of grammars). For this reason, it is essential that these choices are *transparent* and made together with the users of the results. Indeed, specific input/output ratios, such as the EROI or those obtained in Life Cycle Analysis (LCA), represent just one specific realization of the many possible network topologies, and hence can always be contested. Being a semantically-open framework, relational analysis of the metabolic network avoids the generation of potentially misleading results (where the dependence on pre-analytical assumptions is unclear) and permits an open discussion about the relevance and credibility of the assumptions underlying the framing of the analysis.

While relational analysis offers an enormous flexibility in the scope of the analysis (e.g., see (Cadillo-Benalcazar et al., 2020b; Renner et al., 2020a; Ripa et al., 2020) for applications at EU level), the inclusion of further input and output flows/funds in the metabolic processors of the structural elements significantly increases the data requirements. The same is true for including additional levels of analysis. Data availability as well as compatibility of data categorization among different input/output flows is an issue in relational analysis. The triangulation between bottom-up and top-down analysis, as shown in this study, helps to solve this problem. Nonetheless, relational analysis requires significant efforts from the analyst in populating the grammars.

4.2. Practical usefulness of the results for policymaking

Although the case study presented here does not have the explicit goal of informing energy and environmental policy in Ecuador, some conclusions can be drawn. The quality of the oil extracted as measured by API quality in Ecuador has progressively deteriorated in time. The BSW content of the crude oil has progressively increased in time, despite the fact that secondary and tertiary recovery are not practiced to any significant extent. This has resulted in a progressive increase in the volume extracted per unit of oil supply, and concomitant increase in energy use, GHG emission and produced water per unit of oil supply. From 1975 to 2018, GHG emission and produced water per unit of oil supply roughly increased by 30 times. Given the importance of the oil sector for the Ecuadorian economy, extraction is expected to continue and even expand. Recent expansions have seen the exploitation of predominantly heavy oil. This will exacerbate local environmental burdens, notably in the Amazon basin. This should be called to the attention of policy-makers, not only in Ecuador, but also in oil importing countries. Oil importers, such as the European Union, conveniently externalize the bulk of the environmental consequences of their fossil energy use (GHG emission, produced water) to the oil-producing countries.

The Ecuadorian oil extraction system is energy intensive but not labor intensive (e.g., in 2018, the requirement of electricity ranged between 32 and 494 kWh/m^3 of oil, and the labor requirement between 1 and 4 h/m^3 of oil). Indeed, while oil extraction in Ecuador accounted for 18% of the national consumption of electricity (ARCONEL, 2018), it provided employment for less than 1% of the total economically active population in Ecuador in 2018 (INEC, 2019).

The present study highlights the energy-water nexus of conventional oil extraction. Produced water is an inextricable part of the process of oil extraction. It also represents the largest waste stream associated with oil recovery (in terms of volume). Results show that the estimated volume of produced water per unit of oil supply at the national level nearly doubled from 2005 to 2018 and increased by thirty times from 1975 to 2018. During the early oil extraction period in Ecuador, in absence of environmental regulations, oil produced waters were directly dumped, without prior treatment, into the environment, notably in the Amazon basin (Narváez Quiñonez, 2000), or stored in open pits, causing significant environmental damage and health problems for the local population (Hurtig and San Sebastián, 2002; Maurice et al., 2019; San Sebastián and Hurtig, 2004). However, since 2001, with Decree 1215, the Ecuadorian government has prohibited these practices, compelling private and state-owned companies to deposit oil production wastewaters into underground formations (injection wells or reservoirs). Nonetheless, the extent to which these regulations are enforced and the potential risk of leakage from the underground formations into the water table are as yet unclear.

While the reuse of produced water for secondary or tertiary oil recovery provides obvious water conservation benefits (through reduced freshwater consumption) and can help combat environmental pollution (Katchi et al., 2012; Tiedeman et al., 2016), it is currently not practiced to a significant extent in Ecuador as prior on-site treatment of the produced water would be required (Fakhru'l-Razi et al., 2009; Mijaylova Nacheva et al., 2008). This would further increase expenses, energy consumption and GHG emission per unit of net oil supply, thus accentuating the energy trap. Moreover, fresh water supply is currently not a significant problem in Ecuador in the main oil extraction sites (Amazon basin). Other re-uses of produced water have been proposed in areas with severe water shortages, such as irrigation and domestic use, but high treatment and conveyance costs limit their potential (AlAnezi et al., 2013; Echchelh et al., 2018). The problem of the disposal of growing volumes of produced water and the closely related energy trap is not unique to Ecuador, but a growing concern also in major conventional oil producing countries as oil reserves worldwide are ageing and the water cut of the crude oil is progressively increasing. The energy-water nexus is particularly relevant in the Gulf region, where not only the disposal of oil produced water but also the fresh water requirement is a problem (Al-Hubail and El-Dash, 2006).

In order to better inform Ecuadorian energy and environmental policy, it is recommendable that the relational analysis is carried out in co-production with social actors (e.g., local population of the Amazon basin, local and national decision makers) to deliberate about: (i) the inputs and outputs relevant for inclusion in the definition of the metabolic processors; (ii) the specific attributes of the primary energy source relevant for the purpose of the study (e.g., those that affect the performance of the exploitation process); (iii) the set of relations (grammars) relevant for the scaling process; and (iv) the set of indicators for the multi-criteria analysis most suitable for the presentation of the information space to decision makers. In this way, the characterization can be tailored to location-specific contexts, while still maintaining the holistic vision of the large scale. Different social actors, even if faced with the same issue, will undoubtedly opt for different framings.

CRediT authorship contribution statement

Rony Parra: Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Sandra G.F. Bukkens:** Writing - review & editing. **Mario Giampietro:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142371.

References

Ministerio de Energía y Recursos Naturales no Renovables, 2004. Reglamento para el transporte de crudo por el SOTE. Acuerdo Ministerial 14, Registro Oficial 280 de 26 febrero 2004, Ecuador.

AlAnezi, K., Belkharchouche, M., Alali, S., Abuhaimed, W., 2013. Produced water characterization in Kuwait and its impact on environment. Desalin. Water Treat. 51, 302–306. https://doi.org/10.1080/19443994.2012.714524.

Al-Hubail, J., El-Dash, K., 2006. Managing disposal of water produced with petroleum in Kuwait. J. Environ. Manag. 79, 43–50. https://doi.org/10.1016/j.jenvman.2005.05.012.

ARCH, 2020. Estadísticas de la Agencia de Regulación y Control de Hidrocarburos.

ARCONEL, 2018. Bases estadísticas del sector eléctrico.

Bhattacharyya, S.C., Timilsina, G.R., 2009. Energy Demand Models for Policy Formulation: A Comparative Study Of Energy Demand Models, Policy Research Working Papers. The World Bank https://doi.org/10.1596/1813-9450-4866.

de Blas, I., Miguel, L.J., Capellán-Pérez, I., 2019. Modelling of sectoral energy demand through energy intensities in MEDEAS integrated assessment model. Energy Strateg. Rev. 26, 100419. https://doi.org/10.1016/j.esr.2019.100419.

Cabello, V., Renner, A., Giampietro, M., 2019. Relational analysis of the resource nexus in arid land crop production. Adv. Water Resour. 130, 258–269. https://doi.org/10.1016/j.advwatres.2019.06.014.

Cadillo-Benalcazar, J.J., Giampietro, M., Bukkens, S.G.F., Strand, R., 2020a. Multi-scale integrated evaluation of the sustainability of large-scale use of alternative feeds in salmon aquaculture. J. Clean. Prod. 248, 119210. https://doi.org/10.1016/j.jclepro.2019.119210.

Cadillo-Benalcazar, J.J., Renner, A., Giampietro, M., 2020b. A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. J. Environ. Manag. 271, 110944. https://doi.org/10.1016/j.jenvman.2020.110944.

Campos, T., Nonato, M., 2018. Produced water from oil - a review of the main treatment technologies, J Environ Chem Toxicol. Pulsus Group.

Capellán-Pérez, I., de Castro, C., Miguel González, L.J., 2019. Dynamic energy return on energy investment (EROI) and material requirements in scenarios of global transition to renewable energies. Energy Strateg. Rev. 26, 100399. https://doi.org/10.1016/j.esr.2019.100399.

CELEC, 2017. Hito histórico: por primera vez, el sistema petrolero ecuatoriano usa energía eléctrica del Sistema Nacional Interconectado (SNI) [WWW Document]. https://www.celec.gob.ec/transelectric/index.php/18-institucional/contenido-documentos/260-2017-09-05-22-40-46. (Accessed 22 May 2018).

Checkland, P., Scholes, J., 1990. Soft-systems Methodology in Action. John Wiley, Chicester.

Cleveland, C.J., 2005. Net energy from the extraction of oil and gas in the United States. Energy 30, 769–782. https://doi.org/10.1016/j.energy.2004.05.023.

Cleveland, C.J., O'Connor, P.A., 2011. Energy return on investment (EROI) of oil shale. Sustainability 3, 2307–2322. https://doi.org/10.3390/su3112307.

Cleveland, C.J., Costanza, R., Hall, C.A.S., Kaufmann, R., 1984. Energy and the U.S. economy: a biophysical perspective. Science (80-.). 225, 890–897. doi:https://doi.org/10.1126/science.225.4665.890.

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.

Echchelh, A., Hess, T., Sakrabani, R., 2018. Reusing oil and gas produced water for irrigation of food crops in drylands. Agric. Water Manag. 206, 124–134. https://doi.org/10.1016/j.agwat.2018.05.006.

EFE, 2017. Ecuador aspira a elevar producción de petróleo hasta 700 000 barriles en 2021. Diario El Comercio (19 September 2017).

Ministerio de Energía y Recursos Naturales no Renovables, 2018. Ley de Hidrocarburos-1978, Decreto Supremo 2967, Registro Oficial no. 583 (10 May 1978), last modified 21 May 2018. (Ecuador).

European Commission, 2019. The European green Deal. Communication from the commission to the European Parliament, the European council, the council, the European economic and social committee and the Committee of the Regions. COM (2019) 640 final.

Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L.C., Biak, D.R.A., Madaeni, S.S., Abidin, Z.Z., 2009. Review of technologies for oil and gas produced water treatment. J. Hazard. Mater. https://doi.org/10.1016/j.jhazmat.2009.05.044.

Finer, M., Moncel, R., Jenkins, C.N., 2010. Leaving the oil under the Amazon: Ecuador's Yasuní-ITT initiative. Biotropica 42, 63–66. https://doi.org/10.1111/j.1744-7429.2009.00587.x.

Gagnon, N., Hall, C.A.S., Brinker, L., 2009. A preliminary investigation of energy return on energy investment for global oil and gas production. Energies 2, 490–503. https://doi.org/10.3390/en20300490.

Gavenas, E., Rosendahl, K.E., Skjerpen, T., 2015. CO2-emissions from Norwegian oil and gas extraction. Energy 90, 1956–1966. https://doi.org/10.1016/j.energy.2015.07.025.

Gever, J., Kaufmann, R., Skole, D., Vörösmarty, C., 1991. Beyond Oil: The Threat to Food and Fuel in the Coming Decades. University Press of Colorado, Niwot.

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

Giampietro, M., Renner, A., 2020. The generation of meaning and preservation of identity in complex adaptive systems: the LIPHE4 criteria, in: Braha, D., et al (Eds.), Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

Giampietro, M., Mayumi, K., Ramos-Martin, J., 2009. Multi-scale integrated analysis of societal and ecosystem 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., 2013. Energy analysis for a sustainable future: multi-scale integrated analysis of societal and ecosystem metabolism. Routledge, London. https://doi.org/10.4324/9780203107997.

Giampietro, M., Cadillo Benalcazar, J.J., Di Felice, L.J., Manfroni, M., Pérez Sánchez, L., Renner, A., Ripa, M., Velasco-Fernández, R., Bukkens, S.G.F., 2020. Report on the experience of applications of the Nexus structuring space in quantitative story-telling. MAGIC (H2020–GA 689669) project deliverable 4.4.

Greco, S., Ehrgott, M., Figueira, J.R., 2016. Multiple criteria decision analysis, International Series in Operations Research & Management Science. Springer-Verlag, New York, NY. https://doi.org/10.1007/978-1-4939-3094-4.

Hall, C.A.S., Cleveland, C.J., Berger, M., 1981. Energy return on investment for United States petroleum, coal and uranium. In: Mitsch, W.J. (Ed.), Energy and Economic Modelling. Elsevier, Amsterdam, pp. 715–724.

Hall, C.A.S., Dale, B.E., Pimentel, D., 2011. Seeking to understand the reasons for different energy return on investment (EROI) estimates for biofuels. Sustainability 3, 2413–2432. https://doi.org/10.3390/su3122413.

Harati, H.M., 2012. Examination of Produced Water From the Al-Hamada Oilfield. Sheffield Hallam University, Libya.

Heun, M.K., de Wit, M., 2012. Energy return on (energy) invested (EROI), oil prices, and energy transitions. Energy Policy 40, 147–158. https://doi.org/10.1016/j.enpol.2011.09.008.

Secretaría de Hidrocarburos, 2018. Estadística Hidrocarburífera de Crudo Producción.

Hurtig, A.K., San Sebastián, M., 2002. Geographical differences in cancer incidence in the Amazon basin of Ecuador in relation to residence near oil fields. Int. J. Epidemiol. 31, 1021–1027. https://doi.org/10.1093/ije/31.5.1021.

INEC, 2019. Estadísticas laborales, Instituto Nacional de Estadística y Censos [WWW Document]. URL https://www.ecuadorencifras.gob.ec/trabajo/ (accessed 11.1.19).

Katchi, K., Remísio, L., Abdullah, D., 2012. Produced water re-injection, a successful strategy, from pilots to field wide implementation, in: Society of Petroleum Engineers - Abu Dhabi international petroleum exhibition and conference 2012, ADIPEC 2012 - sustainable energy growth: people, responsibility, and innovation. pp. 1248–1258. doi:https://doi.org/10.2118/161307-ms.

Kittner, N., Gheewala, S.H., Kammen, D.M., 2016. Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid. Renew. Energy 99, 410–419. https://doi.org/10.1016/j.renene.2016.07.023.

Kubiszewski, I., Cleveland, C.J., Endres, P.K., 2010. Meta-analysis of net energy return for wind power systems. Renew. Energy 35, 218–225. https://doi.org/10.1016/j.renene.2009.01.012.

Louie, A.H., 2009. More Than Life itself: A Synthetic Continuation in Relational Biology. Walter de Gruyter.

Louie, A.H., 2013. The Reflection of Life. Functional Entailment and Imminence in Relational Biology. Springer, New York.

Louie, A.H.-Y., 2017. Intangible Life: Functorial Connections in Relational Biology. Springer New York, New.

Maddox, K.P., 1978. Energy analysis and resource substitution. In: Roberts, F. (Ed.), Symposium Papers:Energy Modelling and Net Energy Analysis, Colorado Springs, August 21–25, 1978. Institute of Gas Technology, Chicago, pp. 133–144.

Mansure, A.J., Blankenship, D.A., 2010. Energy return on energy investment, an important figure-of-merit for assessing energy alternatives, in: Proceedings of the Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, February 1–3, 2010. p. SGP-TR-188.

Martínez, J., Parra, R., Reis, M., 2016. Una mirada a largo plazo: Análisis multidimensional de la actividad petrolera en ecuador. Cad. PROLAM/USP 15, 53. doi:10.11606/issn.1676-6288.prolam.2016.120127.

Masnadi, M.S., Brandt, A.R., 2017. Climate impacts of oil extraction increase significantly with oilfield age. Nat. Clim. Chang. 7, 551–556. https://doi.org/10.1038/NCLIMATE3347.

Maurice, L., López, F., Becerra, S., Jamhoury, H., Le Menach, K., Dévier, M.H., Budzinski, H., Prunier, J., Juteau-Martineau, G., Ochoa-Herrera, V., Quiroga, D., Schreck, E., 2019. Drinking water quality in areas impacted by oil activities in Ecuador: associated health risks and social perception of human exposure. Sci. Total Environ. 690, 1203–1217. https://doi.org/10.1016/j.scitotenv.2019.07.089.

McIntosh, J.C., Ferguson, G., 2019. Conventional oil—the forgotten part of the water-energy Nexus. Groundwater 57, 669–677. https://doi.org/10.1111/gwat.12917.

MERNNR, 2018. XII Ronda Petrolera Intracampos Ecuador [WWW Document]. URL http://www.rondaspetrolerasecuador.gob.ec/ (accessed 4.29.20).

Mijaylova Nacheva, P., Ramírez Camperos, E., Sandoval Yoval, L., 2008. Treatment of petroleum production wastewater for reuse in secondary oil recovery. Water Sci. Technol. 57, 875–882. https://doi.org/10.2166/wst.2008.202.

Mohr, S.H., Wang, J., Ellem, G., Ward, J., Giurco, D., 2015. Projection of world fossil fuels by country. Fuel 141, 120–135. https://doi.org/10.1016/j.fuel.2014.10.030.

Mulder, K., Hagens, N.J., 2008. Energy return on investment: toward a consistent framework. Ambio 37, 74–79. https://doi.org/10.1579/0044-7447(2008)37[74:EROITA]2.0.CO;2.

Munda, G., 2010. Social multi-criteria evaluation for a sustainable economy. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg. doi:https://doi.org/10.1007/978-3-540-73703-2.

Murphy, D.J., Hall, C.A.S., Dale, M., Cleveland, C., 2011. Order from chaos: a preliminary protocol for determining the EROI of fuels. Sustainability 3, 1888–1907. https://doi.org/10.3390/su3101888.

Narváez Quiñonez, I., 2000. Aguas de formación y derrames de petróleo: la dimensión política en la problemática socioambiental petrolera. PetroEcuador, Quito.

Nijkamp, P., Ouwersloot, H., 1997. Multidimensional sustainability analysis: The flag model. In: van den Bergh, C.J.M., Hofkes, M.W. (Eds.), Theory and Implementation of Economic Models for Sustainable Development. Kluwer Academic Publishers, pp. 255–277.

Nijkamp, P., Rietveld, P., Voogd, H., 1990. Multicriteria Evaluation in Physical Planning. Elsevier Science Publishers B.V, Amsterdam.

Parra, R., Di Felice, L.J., Giampietro, M., Ramos-Martin, J., 2018. The metabolism of oil extraction: a bottom-up approach applied to the case of Ecuador. Energy Policy 122, 63–74. https://doi.org/10.1016/j.enpol.2018.07.017.

Petroamazonas, E.P., 2020. Históricos de producción de petróleo, last accessed May 2020 (Ecuador).

Rashevsky, N., 1954. Topology and life: in search of general mathematical principles in biology and sociology. Bull. Math. Biophys. 16, 317–348. https://doi.org/10.1007/BF02484495.

Renner, A., Giampietro, M., 2020. Socio-technical discourses of European electricity decarbonization: contesting narrative credibility and legitimacy with quantitative story-telling. Energy Res. Soc. Sci. 59. https://doi.org/10.1016/j.erss.2019.101279.

Renner, A., Cadillo-Benalcazar, J.J., Benini, L., Giampietro, M., 2020a. Environmental Pressure of the European Agricultural System: Anticipating the Biophysical Consequences of Internalization. Ecosyst. Serv. (submitted).

Renner, A., Giampietro, M., Louie, A.H., 2020b. Cyborgization of modern social-economic systems: accounting for changes in metabolic identity, in: Braha, D., et al (Eds.), Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

Ripa, M., Cadillo-Benalcazar, J.J., Giampietro, M., 2020. Cutting Through the Biofuel Confusion: A Taxonomy for an Effective Energy Accounting. Energy Strateg. Rev, Submitted.

Rosen, R., 2005. Life Itself: A Comprehensive Inquiry Into the Nature, Origin, and Fabrication of Life. Columbia University Press, New York.

Rosen, R., 2012. Anticipatory Systems: Philosophical, Mathematical, and Methodological Foundations. Springer, New York.

Saltelli, A., Giampietro, M., 2017. What is wrong with evidence based policy, and how can it be improved? Futures 91, 62–71. https://doi.org/10.1016/j.futures.2016.11.012.

San Sebastián, M., Hurtig, A.K., 2004. Oil exploitation in the Amazon basin of Ecuador: a public health emergency. Rev. Panam. Salud Publica/Pan Am. J. Public Heal. 15, 205–211. https://doi.org/10.1590/S1020-49892004000300014.

Serrano-Tovar, T., Peñate Suárez, B., Musicki, A., de la Fuente Bencomo, J.A., Cabello, V., Giampietro, M., 2019. Structuring an integrated water-energy-food nexus assessment of a local wind energy desalination system for irrigation. Sci. Total Environ. 689, 945–957. https://doi.org/10.1016/j.scitotenv.2019.06.422.

Sers, M.R., Victor, P.A., 2018. The energy-missions trap. Ecol. Econ. 151, 10–21. https://doi.org/10.1016/j.ecolecon.2018.04.004.

SISDAT, 2019. Reportes de Información Estadística del Sector Eléctrico, Agencia de Regulación y Control de Electricidad [WWW Document]. http://reportes.regulacionelectrica.gob.ec/. (Accessed 1 November 2019).

Solé, J., García-Olivares, A., Turiel, A., Ballabrera-Poy, J., 2018. Renewable transitions and the net energy from oil liquids: a scenarios study. Renew. Energy 116, 258–271. https://doi.org/10.1016/j.renene.2017.09.035.

Tiedeman, K., Yeh, S., Scanlon, B.R., Teter, J., Mishra, G.S., 2016. Recent trends in water use and production for California oil production. Environ. Sci. Technol. 50, 7904–7912. https://doi.org/10.1021/acs.est.6b01240.

United Nations, 2019. Report of the Secretary-General on the 2019 Climate Action Summit and the Way Forward in 2020.

US Environmental Protection Agency, 2020. Summary of Input on Oil and Gas Extraction Wastewater Management Practices Under the Clean Water Act - Final Report, EPA-821-S19-001.

Yusta-García, R., Orta-Martínez, M., Mayor, P., González-Crespo, C., Rosell-Melé, A., 2017. Water contamination from oil extraction activities in northern Peruvian Amazonian rivers. Environ. Pollut. 225, 370–380. https://doi.org/10.1016/j.envpol.2017.02.063.