Energy 261 (2022) 125256

Contents lists available at ScienceDirect

Energy

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

Securing fuel demand with unconventional oils: A metabolic perspective

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ARTICLE INFO

Keywords:
Energy security
Societal metabolism
Unconventional oils
Refining
Fossil fuels
Oil products

ABSTRACT

A novel methodology is presented for assessing the performance of the oil sector across multiple scales and dimensions of analysis. It focuses on the potential impact of the growing share of unconventional oils in the crude supply mix on energy security through an analysis of the societal energy metabolism. Applying our method at the global level, we find that at the current fuel consumption pattern, an increased exploitation of unconventional oils will cause relative shortages of specific refinery products. The imbalances would be more pronounced if the global fuel consumption pattern would change toward that of the US or the EU. In the former case, gasoline supply would become critical, in the latter diesel. Contrasting performances were found on the selected environmental, technical, or economic criteria for the different simulations analyzed. We conclude that it is of paramount importance to study the oil sector as an integral part of society. In the metabolic view, there are no 'good' or 'bad' primary energy sources (taken in isolation), but a series of trade-offs among various dimensions of performance. Whether or not unconventional oils can provide energy security depends on the overall feasibility, viability, and desirability of the energy metabolic pattern of society.

1. Introduction

The extraction of unconventional oil resources has seen an important increase in the past decade [1–4]. In 2017, ExxonMobil projected that the liquid fuel supply from unconventional sources, notably tight oil, deep-water crudes and oil sands, will increase from 20% in 2010 to 40% in 2040 [3,5]. These projections have been confirmed by Yergin [6], the US Energy Information Administration (EIA) [7] and the International Energy Agency (IEA) [8]. Note that in 2019, oil (conventional and unconventional) still represented 33% of the total primary energy consumed at the global level, which makes it pivotal to energy security [9]. It is also a critical supply chain component for 90% of all industrially manufactured products [10].

Ironically, while there is an agreement on the projected fuel supply from unconventional oils, the definition of what exactly unconventional oils are, is less clear. According to Gordon, echoing the US Department of Energy (DOE), an oil taxonomy cannot be neatly defined as "new oils are emerging along a continuum from conventional crudes to transitional oils to unconventional oils, with their classification varying according to the ease of extraction and processing" [3, p.1]. Murray and Hansen draw the line between conventional and unconventional sources in vague terms: "Conventional oil refers to production from reservoirs that have sufficient pressure, porosity, and permeability to flow freely. Unconventional oil is that which does not flow freely or requires special technologies to extract – as a result, it is more expensive to produce" [11]. The IEA opts for an extensional definition instead, including tight, deep-water, extra-heavy oil, natural bitumen (oil/tar sands), kerogen, gas-to-liquids (GTL), coal-to-liquids (CTL) and additives as unconventional resources [12]. In this paper, we adopt the convention of the IEA.

Unconventional petroleum represents about 70% of known recoverable reserves worldwide, or possibly more [13,14]. Heavy oils and tar sands together represent about 32% of total recoverable resources, tight and ultra-deep oils account for about 10%. Kerogen is the most abundant unconventional resource at 35%, but has lower economic potential and energy content [15]. Given the sheer magnitude of these unconventional resources [16], it is often assumed that we will not run out of oil for centuries and that the only obstacles are "above-ground", i.e., maintaining prices sufficiently high to stimulate technological innovation for their exploitation [17,18]. Nonetheless, several scholars have raised concerns about the timing of this process to smoothly offset the decline of conventional flows [19,20], as well as the upgrading rate of the global refining system, necessary to deal with the increased variability in crude qualities and to transform unconventional resources into useful high-standard products [21–23]. Indeed, in this paper we will show that,

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https://doi.org/10.1016/j.energy.2022.125256
Received 10 November 2021; Received in revised form 6 August 2022; Accepted 22 August 2022
Available online 6 September 2022

despite their abundance, it is not assured that unconventional sources can substitute for conventional ones *at the societal scale*.

The energetic rentability and CO_2 emission of unconventional oils have been studied extensively with different methodologies. For example, Brandt et al. studied the investment of energy carriers and GHG emissions along the whole supply chain of both conventional and unconventional crudes, using Life Cycle Assessment (LCA) and adopting a "barrel forward" perspective [24]. They systematically found that heavy, viscous, and depleted fields are more energy and emission intensive per barrel produced than conventional extraction [25,26]. 'Low quality' crudes (including synthetic substitutes) and the implementation of advanced Enhanced Oil Recovery (EOR), indispensable to extract oil from depleted/difficult reservoirs, invariably come with increased biophysical pressure [27–29]. The Energy Return on Investment (EROI) of extra-heavy oils and tar sands has also shown to be relatively low compared to conventional oils [30,31] and their CO_2 emissions higher [32,33]. Net Energy Analysis (NEA) studies confirm these findings: in the near future, the declining EROIs are expected to exacerbate the "energy cannibalism" (consumption of energy carriers to supply energy carriers) [34,35], with repercussions on the feasibility of a rapid transition away from fossil fuels [36] and on the economy in general [37]. Tight oil has emerged as the most promising source among unconventional oils [16,38–40], with a net energy return and emissions intensity comparable to conventional fields [41], even if the short-cycle technical (and financial) investments needed to maintain operations in time could substantially affect its viability [42]. Potentialities of ultra-deep basins are still largely unknown, but preliminary results indicate low energy returns [43], and the highly complex technologies and infrastructures used in the extraction process present multiple challenges [44,45]. Specific stages of the oil supply chains, such as extraction [46], refining [47–50], and transportation [51], have been analyzed more in detail with the aim of identifying spaces for action to mitigate climate change. Other studies have focused on specific geographic regions [52–54].

The methodological focus in most of the above-cited studies is on the linear life cycle of individual crude feedstocks or oil products assessed in relation to a small number of performance criteria, such as CO_2 emission and/or energy carrier consumption per barrel of crude, or per unit of final product –mono or bi-variate assessments based only on intensive variables [55]. The main concern of these studies is to provide accurate numbers for characterizing the performance of the selected fuel supply chain (determined by a limited set of relevant attributes) within the chosen analytical boundaries (i.e., well-to-wheel or sub-systems like oil extraction, transport and refining). The ultimate purpose generally is to inform energy policies that favor the less energy and emission intense supply chains, crudes and/or final oil products [56–58]. The energy or emission intensity of consuming a unit of a specific oil product (e.g., gasoline) is considered the most relevant attribute of performance and is generally assumed to depend only on the consecutive processes involved in producing that specific product (from well to wheel) [52,59,60]. However, that is a too narrow focus and a shaky foundation to make appropriate policy claims at institutional level. Conundrums like the allocation problem, due to the unavoidable multi-functionality of efficient supply systems, make LCA analyses very dependent of contingent analysts' choices and affect the reproducibility of results [61–64], while a consistent and unified framework is still struggling to emerge [65,66]. Furthermore, it is well known that changes in the demand of oil products may qualitatively affect the complex of extraction and refining [67]. In fact, a product-centered and linearized representation of the energy supply misses the fact that the energy sector is an interactive functional component of society [68,69], the performance of which can only be assessed in relation to the requirements and expectations of the rest of society [70]. From this perspective, supply and consumption can never be disentangled, but intrinsically co-evolve in time [68,71,72]. When dealing with a complex set of energy transformations, in which internal loops generate impredicative causal relations, an excessive simplification of the representation carries the risk of missing relevant aspects (economic, social, ecological) of the problem [68,73]. Here lies the Achilles heel of LCA: societal consumption patterns are not embedded into the LCA linear representation. But the societal consumption practices bound the space of possible supply pathways and define their size; and hence, the quality of the *coupling* between supply and requirement affects *qualitatively* the integrated performance of the oil metabolism.

In this work, we attempt to fill this gap by adopting the perspective of societal metabolism [69,74], and by conceptualizing the oil sector as an integral part of human society. We propose a novel methodology to assess the performance of the changing oil sector that is based on the semantically open accounting framework – Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) – and that provides an integrated representation of the societal metabolism of oil. More in particular, we explore the entanglement between patterns of crude oil exploitation, the resulting product slates made available by refiners (on the supply side), *and* the oil products required in the different end-uses in society (on the demand side). We identify potential constraints in the coupling of the supply and requirement of those oil products. We not only consider energy carrier consumption and CO_2 emission as relevant attributes, but various other criteria of performance related to the desirability, viability, and feasibility of the oil metabolism. The focus of our approach is not on the linear life cycle of individual oil product(s), but on the *coupled* production and consumption patterns of oil products at a higher level of abstraction. We illustrate our approach numerically by exploring the global oil metabolism with varying contributions of unconventional oils.

The paper is organized as follows: In section 2, we describe our methodological approach and define the descriptive domain of the analysis, as well as the production and consumption patterns of the oil products considered. In section 3, we illustrate the type of results yielded by the approach at the global level. In section 4, we discuss the relevance and novelty of our approach as well as its shortcomings. Section 5 concludes.

2. Methodology

2.1. A metabolic perspective on energy security

From a metabolic perspective, energy security refers to the sustainability of the societal energy metabolism, in line with the conceptualization of "low vulnerability of vital energy systems" proposed by Cherp and Jewell [75]. Energy security thus is a property of the whole system, rather than a mere attribute of the energy supply chains or primary sources exploited (as is the working assumption in LCA). Giampietro et al. [76] has proposed four interdependent criteria for assessing the sustainability of the energy metabolism of complex social-ecological systems:

1. Feasibility: compatibility of the metabolic pattern with external biophysical (environmental) constraints beyond human control.
2. Viability: compatibility with internal biophysical, techno-economic constraints under human control.
3. Openness of the system (e.g., imports and exports required for sustaining the metabolic pattern).
4. Desirability: compatibility of the metabolic pattern with societal expectations.

Each of these four criteria spans a wide range of possible performance dimensions (see section 2.2.2). This is an important improvement compared to the mono-dimensionality of LCA analysis, focusing mostly on CO_2 emission.

Note that MuSIASEM has been purposefully developed to study the energy and food metabolism of complex social-ecological systems [68,77]. In MuSIASEM, the energy sector is seen as a fundamental constituent component of the social-ecological system. It is the part of the system that exploits Primary Energy Sources (PES) from the environment to supply the energy carriers required (in quantity and quality) by the rest of society and by the energy sector itself (energy-for-energy internal loop). Therefore, the energy sector constitutes an important interface between the ecosphere (environment/ecological system) and the anthroposphere (socio-economic system). To explore energy security within the conceptual framework of MuSIASEM, we consider the impredicative relation between the energy supply – the transformation of PES into energy carriers in the energy sector – and the societal requirement of specific energy carriers to meet the desired end uses, including those of the energy sector itself. On the supply side, multiple combinations of pathways of PES exploitation can be used to produce a given profile of energy carriers (in quantity and quality). On the consumption side, different combinations of energy carriers (in quantity and quality) can be employed to express a specific set of end uses. The quantitative mapping between the energy carrier supply and requirement profiles generates possible metabolic states for the energy sector. The option space is composed by those states that are compatible with the viability and feasibility constraints and still allow a functional and desirable metabolic pattern for the society as a whole.

Note that in this paper we illustrate our approach at the global scale, and hence we do not consider the criteria "openness". However, it is important to stress that at the national level, the extent of openness of the system will affect not only the feasibility and viability of the metabolic pattern – through the import of resources and export of environmental impacts – but also its desirability: is the dependence of societal energy security on imports and exports desirable?

In Fig. 1, we elaborate the above conceptualization specifically for the oil metabolism, the sub-system of the energy metabolism that is specifically concerned with oil exploitation. The society as a whole represents the high end of the system's hierarchical structure (level $n+2$) and the instances of oil fields and refineries represent the low end (level *n-2*). Note that with the term 'hierarchy' we do not imply unidirectional power relations, but mutually entangled relations in both directions [78]. End uses at the higher levels determine meaning and boundaries (the space of opportunities) for the activities taking place at lower levels, but at the same time the very existence of the upper levels is determined by what is biophysically possible (in terms of extraction and refining) at the lower scales (the space of realizations). The dynamic equilibrium in this specific set of hierarchical relations emerges at the interface between the oil products supplied and those required by the society, net of the internal energy-for-energy loop (level $n \leftrightarrow$ level $n+1$). Any specific societal configuration entails specific requirements of oil products (level $n+1$), such as gasoline and kerosene for motorized transport or petrochemical feedstocks and heavy distillates for industry. On the other hand, the set of possible sequential pathways of extraction and refining, described by the structures and functions of the oil sector at level *n-1*, depends on geological-environmental constraints (e.g., oil field characteristics, water, and land availability) and techno-economic capacities (e.g., technology, capital, labor). We thus have a forced profile of required inputs (and resulting wastes) for operating the supply pathways and a forced oil product slate as output (a given profile of gasoline, diesel, and other types of fuels).

2.2. Oil sector taxonomy and multidimensional spaces across scales

To implement the metabolic perspective, we first provide a definition of the taxonomy of oil sequential pathways (extraction and refining) and pertinent categories of energy forms and dimensions of performance relevant for our purpose of assessing energy security in relation to viability and feasibility criteria. Following, extraction and refining types are characterized numerically, based on real instances, and possible sequential pathways are assessed.

2.2.1. Oil sector taxonomy

To date, the commercially most important unconventional oils are (i) tight oil, (ii) extra-heavy and tar sands (API gravity below 15, following the categorization given in Ref. [24]), (iii) ultra-deep water oils [44,79] and (iv) depleted fields, where advanced EOR techniques are used to extract the crude. We label here only the former three categories as 'unconventional'. Depleted fields are treated as a separate category, even if often considered 'unconventional', given that the aging process is not the focus of the present work. We do not consider unconventional oil

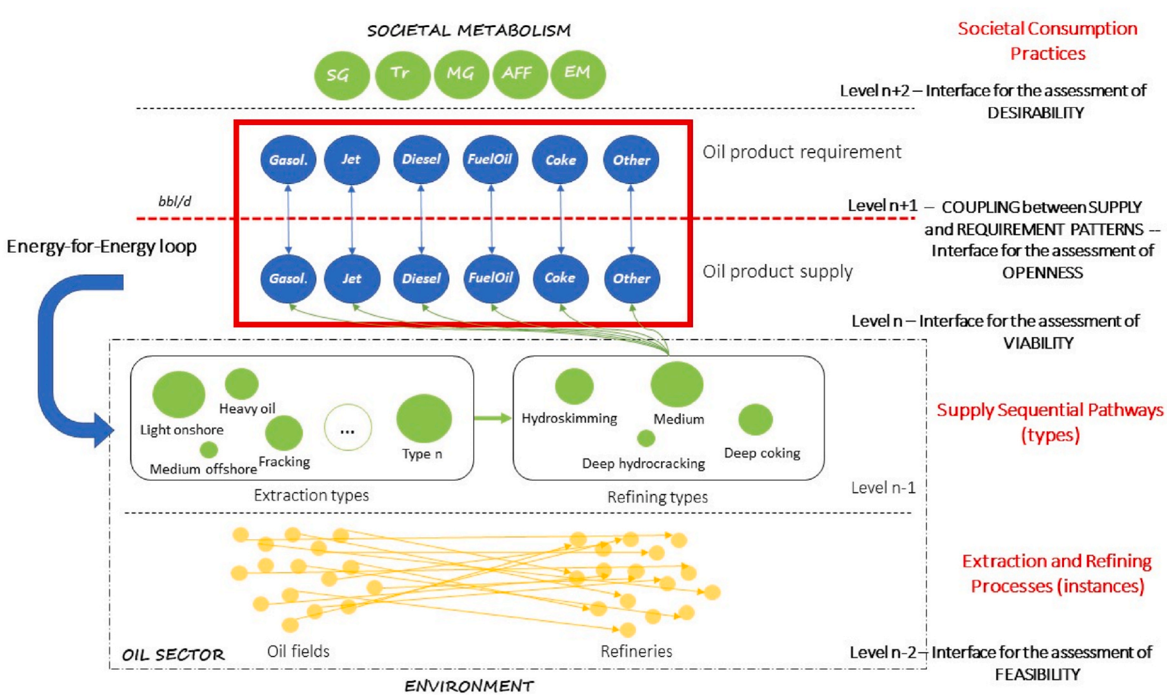

Fig. 1. Multiscale representation of the oil sector. Acronyms: SG 'Service and Government', Tr 'Transport', MC 'Manufacturing and Construction', AFF 'Agriculture, Forestry and Fisheries', EM 'Energy and Mining' (excluding the oil sector).

typologies that have not been proved commercially feasible or relevant (kerogen, methane hydrates, synthetic oils).

Both conventional and unconventional oil exploitation is typically composed of two basic steps:

(i) Extraction and transport (upstream and midstream)
(ii) Refining and distribution (downstream).

In this work, transport and distribution are not accounted for given that (i) their input requirement (and waste production) is negligible compared to that of extraction and refining, and (ii) we focus on the global level to illustrate our approach in general lines (accounting of transport and distribution would require a geographical contextualization of trade).

Extraction types are selected based on their technical and biophysical relevance for the supply process and categorized according to the following attributes (see Table 1):

1. API Gravity: Light, Medium or Heavy & Extra-heavy oils
2. Water content: Low Water or Watery
3. Location: Onshore or Offshore.

For this study, heavy and extra-heavy oil is defined by an API gravity between 10 and 15, and kept separate from tar sands, with API gravity <10.

In addition, a further five extraction types are considered (see Table 1):

- Fracking and ultra-deep typologies, being characterized by highly specialized extraction technologies with different biophysical requirements and environmental burdens
- Depleted and heavily depleted typologies, being characterized by a long history of exploitation, where the effects of depletion are evident
- Tar sands, having peculiar coal-like characteristic that affect every aspect of their exploitation and the final products

Regarding refining, depending on the API gravity and sulfur content of the crude, four different types can be identified:

1. Hydroskimming conversion
2. Medium conversion
3. Deep conversion – coking
4. Deep conversion – hydrocracking

Complexity of refining increases with API gravity and sulfur content: more energy and technical intensive processes are required to transform heavier and dirtier oils (see Table 1).

2.2.2. Pre-analytical choice of relevant dimensions of performance

In line with MuSIASEM conventions, we consider a set of flow and fund variables that are relevant for characterizing the extraction and refining processes, where the concepts of 'flow' and 'fund' are defined as follows [80]:

- Flows: entities that do not maintain their identity during the analytic time frame; they are metabolized by funds to become something else. They describe what the system does.
- Funds: entities that maintain their identity during the analytical time frame; they metabolize flows and represent the structure of the system. They describe what the system is made of.

The following flows are considered in the analysis:
Input flows:

- Net consumption of natural gas and refinery fuel gas (MJ/bbl)
- Net and indirect (associated with imports) consumption of electricity (MJ/bbl)
- Net and indirect consumption of diesel (MJ/bbl)
- Net consumption of coke – only for refining (MJ/bbl)
- Net water consumption (bbl_{water}/bbl_{oil})
- Capital expenditures (€/bbl)

Output Flows:

- In-site and indirect CO_2 emissions ($kgCO_2eq/bbl$)
- Extracted quantity of oil (bbl/d)
- Refined quantity of oil (bbl/d)

Note that indirect consumption is related only to extraction, while net coke consumption is relevant only for refining and tar sands extraction.

As for input funds, we selected:

- Land use (ha/bbl) – (only for extraction)
- Labor (hrs/bbl)
- Fixed assets (€/bbl)

Lastly, the product slate (%) reflects the relative composition of the oil products. The product slate eventually supplied by viable production patterns is essential to assess the supply-requirement coupling. The set of oil products considered is the following:

- Gasoline
- Jet fuel
- Diesel
- Fuel oil
- Coke
- Other oils

Coke and other oils are grouped together under the label 'other products' for a coherent mapping between supply and requirement categories (see Supplementary Material).

2.2.3. Multidimensional descriptive spaces and combined production functions

We define $\boldsymbol{d_p}$ as the array of performance benchmarks (the descriptive domain, see Fig. S1) at process-level, $\boldsymbol{d_{sp}}$ at the level of sequential pathway and $\boldsymbol{d_{cs}}$ at the level of the whole (combined) supply:

$$\boldsymbol{d_x} := \{(d_1, d_2, \ldots, d_n)\} \mid d_i \in \boldsymbol{R}$$

Note that $\boldsymbol{x}$ stands for the level at which the space $\boldsymbol{d_x}$ can be defined. $\boldsymbol{d_p}$ quantifies the pressures for single processes taking place inside the oil metabolism, such as extraction or refining. It is composed by the input/output flow and funds described in Section 2.2.2, except for the extracted and refined quantities of oil that are used as scaling factors to maintain the coherence of size across scales. $\boldsymbol{d_{sp}}$ is calculated by summing up the lower-level benchmarks, since it quantifies pressures resulting from oil operations carried out in series. To calculate $\boldsymbol{d_{cs}}$ we need to know the actual mix of sequential pathways employed inside the oil sector. This piece of information is strictly context dependent. We call $\boldsymbol{m}$ the vector that defines the relative composition of sequential pathways:

$$\boldsymbol{m} := \frac{1}{2}\{(m_1, m_2, \ldots, m_v)\} \,\Bigg|\, m_i \in \boldsymbol{R} \wedge \sum_{1}^{v} m_i = 1$$

With v identifying viable combinations of extraction and refining typologies (e.g., heavy and extra-heavy oils cannot be refined with hydroskimming refining facilities).

Thus, $\boldsymbol{d_{cs}}$ can be calculated as follows:

Table 1
Library of sequential supply pathways of oil products – matrix space ***F***

LIBRARY OF PRODUCTION FUNCTIONS		MJ/bbl				kgCO2eq/bbl	bblwater/bbloil	ha/bbl	€/bbl		h/bbl	Product slate %					
Oil Fields Types	**Associated Refining**	**Natural gas**	**Electricity**	**Diesel**	**Coke**	**GHG emissions**	**Net water use**	**Land use**	**CapEx**	**Fixed assets**	**Labor**	**Gasoline**	**Jet Fuel**	**Diesel**	**Fuel Oil**	**Coke**	**Other oils**
Light Low Water Onshore	Hydroskimming	387	13	7	0	42	2,18	0,45	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	545	19	7	25	56	2,18	0,45	15	106	0,16	36%	19%	18%	0%	0%	26%
Light Low Water Offshore	Hydroskimming	473	17	13	0	50	8,79	0,04	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	630	23	13	25	63	8,79	0,04	15	106	0,16	36%	19%	18%	0%	0%	26%
Medium Low Water Onshore	Hydroskimming	496	12	8	0	63	4,32	0,45	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	653	18	8	25	77	4,32	0,45	15	106	0,16	36%	19%	18%	0%	0%	26%
Medium Low Water Offshore	Hydroskimming	330	12	5	0	37	3,20	0,04	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	487	17	5	25	50	3,20	0,04	15	106	0,16	36%	19%	18%	0%	0%	26%
Light Watery Onshore	Hydroskimming	722	47	6	0	95	8,83	0,90	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	879	53	6	25	109	8,83	0,90	15	106	0,16	36%	19%	18%	0%	0%	26%
Light Watery Offshore	Hydroskimming	820	18	5	0	92	7,88	0,08	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	977	23	5	25	105	7,88	0,08	15	106	0,16	36%	19%	18%	0%	0%	26%
Medium Watery Onshore	Hydroskimming	654	23	14	0	17	3,24	0,90	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	811	29	14	25	107	3,24	0,90	15	106	0,16	36%	19%	18%	0%	0%	26%
Medium Watery Offshore	Hydroskimming	471	21	4	0	48	4,24	0,08	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	628	27	4	25	62	4,24	0,08	15	106	0,16	36%	19%	18%	0%	0%	26%
Ultra deep	Hydroskimming	496	15	40	0	68	3,91	0,04	16	105	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	654	21	40	25	82	3,91	0,04	16	105	0,16	36%	19%	18%	0%	0%	26%
Depleted fields	Hydroskimming	728	44	7	0	72	4,47	1,80	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	886	50	7	25	86	4,47	1,80	15	106	0,16	36%	19%	18%	0%	0%	26%
Heavily depleted fields	Medium Conversion	2391	26	1	25	158	8,86	3,61	15	106	0,16	36%	19%	18%	0%	0%	26%
	Deep Conversion - Coking	2911	42	1	49	199	8,97	3,61	18	126	0,11	44%	11%	31%	0%	10%	3%
	Deep Conversion - Hydrocracking	3215	48	1	41	221	8,99	3,61	18	126	0,11	38%	11%	40%	0%	8%	3%
Fracking	Hydroskimming	405	12	17	0	77	0,63	0,98	16	105	0,16	29%	23%	10%	10%	0%	28%
Heavy&Extra-heavy	Medium Conversion	1147	27	12	25	113	5,70	0,90	20	213	0,18	36%	19%	18%	0%	0%	26%
	Deep Conversion - Coking	1667	43	12	49	154	5,80	0,90	20	213	0,18	44%	11%	31%	0%	10%	3%
	Deep Conversion - Hydrocracking	1970	50	12	41	176	5,83	0,90	20	213	0,18	38%	11%	40%	0%	8%	3%
Tar sands	Hydroskimming	1687	57	738	136	146	1,87	1,01	20	213	0,18	29%	23%	10%	10%	0%	28%
	Medium Conversion	1845	63	738	161	160	1,87	1,01	20	213	0,18	36%	19%	18%	0%	0%	26%
	Deep Conversion - Coking	2365	79	738	186	200	1,97	1,01	20	213	0,18	44%	11%	31%	0%	10%	3%
	Deep Conversion - Hydrocracking	2668	86	738	177	222	2,00	1,01	20	213	0,18	38%	11%	40%	0%	8%	3%

$$d_{cs} = m \times D_{sp}$$

where D_{sp} represents the sequential pathway matrix $v \times n$. The rows of D_{sp} are composed by the arrays d_{sp_i} for every possible sequential pathway $i = 1, 2, \ldots, v$ operating in the system; the columns are the dimensions of performance (the cardinality of d_{sp_i}).

Finally, we define s as the set of oil products, the product slate:

$$s := \{(s_1, s_2, \ldots, s_t)\} \left| s_i \in \mathbf{R} \wedge \sum_1^t s_i = 1 \right.$$

where t is the number of final oil products. As before, s can be defined at three different levels –process (s_p), sequential pathway (s_{sp}), combined supply (s_{cs}). The overall product slate (s_{cs}) is a function of the relative combination of supply pathways m in the total mix. The arrays introduced so far are *multidimensional spaces,* representing the domain (d) and co-domain (s) of our analysis.

The relational entailment between typologies of processes and/or sequential pathways, spaces of performance and product slates can be qualitatively coded by a set of production functions that associate every viable process/sequential pathway with its profile of pressures and outcome of oil products. The space of production functions (at the level of sequential pathways) can be defined by the following associative relation:

$$F : D_{sp} \rightarrow S_{sp} \wedge F \in \mathbf{R}^{v\,x\,(n+t)} \left| f_k = \left(d_{sp_i} \middle| s_{sp_i}\right), \forall s_{sp_i} \in S_{sp} \wedge d_{sp_i} \in D_{sp} \wedge f_k \in F \right.$$

It informs us about how PES are converted into useful energy carriers (Table 1). There is some flexibility in the oil production process – refiners can decide to increase or decrease shares of high margin products depending on market conditions (changes of the array m) – but not everything is possible. The library of sequential pathways in Table 1 accounts for this variability.

A variety of datasets has been employed to construct the library of sequential pathways. The energy carrier requirements and GHG emissions of the oil sector itself are from Ref. [24]. To the best of our knowledge, robust water consumption data are not available. Hence, water consumption data have been collected from different sources [81–85] and processed as explained in the supplementary material (section S2.2). The metabolic benchmarks of capex, fixed assets and labor have been obtained from the oil companies ENI, Shell, Suncore and Chesapeake balance sheets and cash flows [86–90]. Land use intensities have been derived from typical values in the Uppsala Giant Oil Field Database [91–93]. Further details and more references are available in the Supplementary Material, Section S2.

2.3. Confronting supply and consumption patterns of oil products

Having defined the multiple levels of performance on the supply side, we can now embed the societal consumption patterns into the representation, and explore potential mismatches between production and requirement of oil products at societal level. To this purpose, we built four combined production functions with different contributions of unconventional pathways: (i) 'current supply' (baseline); (ii) 'unconventional light supply', assuming an increased contribution from fracking and ultra-deep pathways; (iii) 'unconventional heavy – coking supply', assuming an increased production from heavy, extra-heavy oils and tar sands using coking facilities in refining; and (iv) 'unconventional heavy – hydrocracking supply', similar to the previous one but using hydrocracking facilities for refining. We further consider three different societal consumption patterns of the main oil products. The first is the baseline situation, where the consumption pattern is assumed equal to the current global production pattern. The other two reflect the current oil product consumption profiles of the EU and the USA. Note that we do not seek to assess oil security for the EU or the USA, but simply use consumption profiles typical of those geographic regions to explore potential future bottlenecks in response to changing oil product production patterns.

2.3.1. Product slates associated with production functions

The four production functions have been generated by combining possible sequential pathways (Table 1), using the relative contributions (viable arrays m) reported in Tables S8–S9 (Supplementary Material). The associated multidimensional spaces are described in Tables 4 and 5. Each production function provides as output a different profile of product slate (Table 2). Note that the selected combined production functions are not meant to represent any realistic scenario, but are 'what if' simulations to explore the multidimensional spaces D_{cs} and S_{cs}. We perform our exercise at the global scale: the size of the global oil sector is assumed to be 105 million barrels of crude per day, following the IEA's forecast "State Policies Scenario 2030" [8]. The baseline case is constituted by the current global supply pattern and has been adapted from Ref. [94] with the following modifications: (i) we introduced the 'tar sands' pathway that accounts for 2% of the global production [31]; and (ii) heavy and extra-heavy pathways (grouped) are assumed to account for an 11% share rather than 14%. As for coupling extraction and refining, we took again [94] as reference, except for the refining of tar sands that is equally divided (50% each) between hydroskimming (syncrude oil) and deep conversion (dilbit) refining (Table S9). The relative refining shares for each crude have been kept constant for all four cases considered.

The other three simulations are based on the baseline, but with a progressive increase in the relative share of unconventional oils. The overall unconventional share on the global crude supply increases from 22% in the baseline supply to 60% in the unconventional supply simulations (see Table S8 and Figs. S2–S3):

1. 'Unconventional light' supply: the combined share of fracking and ultra-deep is increased from 8% to 60% of total global crude production.
2. 'Unconventional heavy – coking' supply: the contribution of heavy & extra-heavy oils and tar sands to the global crude production is assumed to be 40% and 20% respectively. The downstream refining is assumed to be done entirely with coking facilities.
3. 'Unconventional heavy – hydrocracking': the same as the previous one, but the refining is entirely performed with hydrocracking facilities.

The composition of final oil products in the four simulations (combined production functions) is shown in Table 2. Some considerations about performance are relevant here. First, note that in the unconventional light production function, the internal requirement of coke cannot be satisfied. Second, for the calculation of the internal energy loop (the differences between gross and net in Table 2), we focused only on crude oil products. We did not consider the internal use of the associated natural gas – extracted together with oil from oil fields – as input for crude production. Natural gas is a by-product of oil production and is the most widely used energy carrier in the extraction and refining processes [94], hence relevant for the calculation of the EROI. As shown in Table S13, without considering associated natural gas, unconventional heavy pathways already use about 10% of their output of energy carriers for internal consumption (EROI = 10) and considering also natural gas would further reduce the overall benchmarks to well below 10 (6.5 according to Ref. [36]). Obviously, the numbers in Table S13 and Table 2 (describing the efficiency and size of the internal energy loop with different metrics) are not a realistic forecast [39], but serve to flag potential problems of an extensive exploitation of unconventional oils.

2.3.2. Typologies of societal consumption patterns of oil products

The requirement of energy carriers depends on societal end uses. However, for our illustration, we consider simplified patterns of oil product requirements without mapping them to specific societal sub-

Table 2
Typologies of product slate (matrix space S_{cs}), *i.e., the compositions of oil products produced in the four combined production functions. 'Net' and 'gross' refers to, respectively, the inclusion or exclusion of the internal oil-for-oil loop in the analysis.*

	Gasoline	Jet Fuel	Diesel		Fuel Oil		Coke		Other oils
	Net	Net	Gross	Net	Gross	Net	Gross	Net	Net
Current	35%	19%	18%	17%	2%	2%	1.1%	0.4%	24%
Unconventional light	33%	21%	14%	14%	5%	5%	0.1%	**−0.2%**	27%
Unconventional heavy coking	38%	16%	22%	17%	2%	1%	5%	3%	17%
Unconventional heavy hydrocracking	36%	16%	26%	21%	2%	1%	4%	2%	16%

sectors and end-uses, nor do we consider trade. The set of societal requirements (consumption), quantifying the expectations of the rest of society from the oil sector, is defined as the multidimensional space $\boldsymbol{c}$:

$$\boldsymbol{c} : = \{(c_1, c_2, \ldots, c_t)\} \mid c_i \in \boldsymbol{R}$$

We selected three arrays of societal oil product consumption (See Table 3):

1. World, where the consumption equals the current global supply of oil products – a proxy for the current consumption at the global level.
2. US, describing the current consumption pattern of oil products of the USA.
3. EU, describing the current consumption pattern of oil products of the EU.

The consumption of oil products in the baseline situation ('world') reflects the current supply scenario obtained from Ref. [95], assuming that consumption and production match at the global level (net of stocks). The US typology is based on data from the EIA [96], and the EU one is calculated from Ref. [97]. More details are available in the Supplementary Material.

Coupling these multiple consumption patterns to the four selected combined production functions allows us to anticipate the effects on the integrated performance space. The *integrated performance space* resulting from the coupling between the product slate j (production function j) and societal requirement r is defined as:

$$\boldsymbol{ip} : = \{(ip_1, ip_2, \ldots, ip_n)\} \mid ip_i = e_{jr} \cdot d_i \ \wedge \ 1 \leq i \leq n, \ ip_i \in \boldsymbol{R}$$

Where e is the *coupling factor* that we define in the next section.

The integrated performance space can be interpreted as the multidimensional space of the societal pressures associated with the consumption of one barrel of oil products, given a determined production function. It describes the overall performance of the oil metabolism at the level of society. When *simultaneously* accounting for the supply and consumption patterns of multiple products that are *jointly produced*, intensive supply benchmarks (space $\boldsymbol{d_{cs}}$) account for costs from the perspective of producers, but consumption pressures (space $\boldsymbol{ip}$) may differ from the perspective of consumers. The mismatch between $\boldsymbol{d_{cs}}$ and $\boldsymbol{ip}$ consists in the additional pressures (i.e., the environmental, socio-economic, and technical) of the oil products supplied but not required.

Table 3
Societal requirement patterns of oil products – matrix spaceC

Oil product	World	US	EU
Gasoline	35%	45%	*16%*
Jet fuel	19%	8%	*3%*
Diesel	18%	20%	*54%*
Fuel Oil	2%	2%	*4%*
Other products	25%	25%	*24%*
Total	**100%**	**100%**	**100%**

Note that these profiles are special instances based on current 'real' consumption patterns inside delimited geographical regions. They serve to explore what would happen if the global oil product requirement would take the form of current US or EU consumption patterns.

2.3.3. Matching production and consumption: 'crack limiting flow' and 'coupling factor'

Given the product slate s_{cs} associated with the production function f_k, and the array C_j of societal requirement, the associated Coupling Factor (CF) can be defined as:

$$e_{kj} = \max\left(c_i / s_i\right)_{i=1}^{t}$$

The Crack Limiting Flow (CLF) is the oil product associated with the highest Coupling Factor.

Hence, CLFs are identified by the maximum distances between points of requirement and production for the same oil product (gasoline, jet fuel, diesel, fuel oil, coke & heavy ends), as is illustrated in Fig. 6. CFs can be seen as the quantitative supply adjustments needed to balance (limited) supply and requirement.

At the global level and in the long term, total consumption and production must match, net of stocks (not relevant in the long term since oil products decay over time). In practice, product slate and requirement (the formal attributes that account for, respectively, the quality of the PES exploited and the quality of the energy carriers required) will be different, thus potentially creating surplus of all the oil products other than the limiting one. Hence, in a closed system (as is the global system), coherence is given by adjustments up to coupling factors and net of the energy loop, generating the performance indicators of space $\boldsymbol{IP}$ and giving the correct size of the supply system (i.e., barrel of oil products produced per day). The internal consumption of energy carriers needs to be subtracted from the total output of the oil sector in order to calculate coupling factors, since the oil sector is part of society itself. Maintaining non-equivalent intensive (metabolic benchmarks, normalized per barrel) and extensive descriptions is crucial to check the coherence across scales.

We focus here on the supply side, but it is equally well possible to approach the analysis from the consumption side, to explore changes in social practices.

3. Results

In this section, we explore the metabolic network presented in Fig. 1 and the performance benchmarks of multidimensional spaces $\boldsymbol{D_{cs}}$ and $\boldsymbol{IP}$ resulting from the selection of the four combined production functions. Performance benchmarks at each scale are determined by (i) the library of sequential pathways, (ii) the dynamic coupling between production and consumption of oil products; and (iii) the size of the system – the barrels produced per day. Once these three factors are established, the absolute size of the system required to meet oil products requirement can be recursively 'adjusted' based on the crack limiting flow. The multiple dimensions relate to different domains (socio-economic, techno-biophysical and environmental), and hence the performance assessment will inform stakeholders about the feasibility and viability of the oil metabolism.

3.1. Supply side performance – space $\boldsymbol{D_{cs}}$

Supply benchmarks (pressures) for the space $\boldsymbol{D_{cs}}$ are reported in Tables 4 and 5; a compact radar visualization is shown in Fig. 2. Note that the scale in Fig. 2 is logarithmic, hence differences are bigger than they appear on first sight. The dimensions associated with the viability criterion are: (i) hours of human labor (fund); (ii) fixed assets of oil companies (fund); (iii) profile of energy carriers requirement (quality and quantity) (flows); (iv) capital expenditures (capex) (flow). Dimensions in the feasibility domain comprise land use (fund), net water consumption (flow) and GHG emission (flow). The related gross and net (corrected for the internal energy-for-energy loop) output of oil products S_{cs} is shown in Table 2.

The unconventional light supply pattern (in red) shows benchmarks similar (or better) to those of the baseline pattern (Fig. 2). The performance for fixed assets and land use is comparable (Figs. S6 and S12), but it is less intensive with regard to fuels and labor investment (Fig. 8 and S4). On the other hand, the unconventional heavy supply patterns show major increments across the entire set of benchmarks, both for coking (grey) and hydrocracking (black) (the grey and black pattern largely overlap in Fig. 2).

Fig. 3 shows the consumption of energy carriers per hour of labor (flow-fund benchmark, in MJ/h), a proxy of power capacity available per worker, net of the utilization factor, and per hectare of land (in MJ/ha), for the four combined production functions. A larger share of unconventional light sequential pathways in the supply mix improves both indicators, while a larger share of heavy ones deteriorates the situation, especially the performance of diesel utilization. In the same manner, Fig. 4 shows the CO_2 emissions and net water consumption per hectare, as well as the fixed assets and capex per hour of labor. The unconventional light production function performs better than the baseline on all indicators, except for capex (no changes), while the unconventional heavy supply typologies score worse, except for net water consumption.

3.2. Integrated supply-consumption performance – space *IP*

Using the library of sequential pathways and the overall size of the system (105·10^6 bbl/d), we assessed the energy-for-energy internal loop – i.e., the oil products consumed by the oil sector to produce the oil products – of the combined production functions associated with the product slate typologies (Tables S12–S13). It is important to assess this internal loop as it affects the net societal requirement for oil products. We then compared the *net* oil product (EC) supply with oil product requirements for all the combinations between the four production and three consumption typologies, thus identifying the CFs (see Fig. 5, note that some product slates and societal requirements overlap). Corresponding CLFs are reported in Table 6. Note that CFs would be higher if not corrected for the internal requirements of the energy sector.

The concept of CLF is useful to anticipate mismatches in net supply and requirement patterns. At the global scale (closed system), mismatches cannot be offset by trade, but only through increasing total supply. To better grasp the extent of the mismatch, we calculated the adjusted supply by scaling up production to meet the limiting flow, as shown in Fig. 6, and the associated integrated performance space ***IP*** (Fig. 7).

In Fig. 6, the baseline for comparison is represented by the current product slate coupled with the current oil product requirement (‘world’, green bar). The equilibrium is established at 105 million barrels of crude per day. Changing product slate typology (combined production function – red, green, black bars) generates a marginal increase in oil sector size (daily production of barrels of crude) as indicated in black on top of the bars. The percentual increase due to changes in societal requirement pattern (World → US → EU) is indicated in light blue. Note that the societal requirement is far more influential than the combined production function for matching oil product supply and requirement. For instance, if the whole world would adopt the EU consumption pattern, we would run into serious problems, as shown in Fig. 7 for the environmental pressures (the full integrated performance space is illustrated in the Supplementary Material). The more a society ‘specializes’ its consumption on a restricted set of refinery products (e.g., low-sulfur diesel in the EU or gasoline in the USA), the more difficult it becomes to match production and consumption patterns, thus facing potential consequences of an increased biophysical and economic pressure of an ‘unbalanced’ oil sector.

Table 5
Supply benchmarks – space D_{cs} – of the combined production functions: feasibility dimensions.

	GHG emissions kgCO2eq/bbl_{oil}	Net water use bblwater/bbl_{oil}	Land use ha/bbl_{oil}
Current	80	3,75	3,55
Unconventional light	78	3,23	5,34
Unconventional heavy coking	125	4,47	8,13
Unconventional heavy hydrocracking	135	4,48	8,13

4. Discussion

4.1. Novelty and strength of the proposed approach

Our metabolic perspective and conceptualization of energy security as the sustainability of the societal energy metabolism offer important advantages over traditional LCA analysis. As observed in the introduction, LCA is marked by a linear product-centered approach, where every oil product is considered individually, independent from the context – hence forcing analysts to use heavy contingent assumptions to deal with joint production and consumption issues and multi-functionality of energy systems – and by a limited performance space (e.g., considering only CO_2 emissions). It typically establishes a linear direction of causality over the quantitative relations and therefore cannot handle the existence of mutual dependence between different variables (impredicativity). We overcome these issues by enlarging the analytical boundaries of the system (our focus is on supply and requirements *patterns*, rather than individual products) and by considering a multidimensional performance space to assess the feasibility, viability, and desirability of the societal oil metabolism. Indeed, our combined supply space (D_{cs}) and integrated performance space (***IP***) constitute a fundamental difference with the LCA approach.

The use of flows and funds, non-equivalent representations (intensive and extensive), and multiple analytical dimensions is another important novelty of our approach. It allows us to:

1. Assess the comparative performance of different energy supply systems (intensive)

Table 4
Supply benchmarks – space D_{cs} – of the combined production functions: viability dimensions.

	Natural gas MJ/bbl_{oil}	Electricity MJ/bbl_{oil}	Diesel MJ/bbl_{oil}	Coke MJ/bbl_{oil}	CapEx €/bbl_{oil}	Fixed assets €/bbl_{oil}	Labor h/bbl_{oil}
Current	759	25	24	25	14	113	0,13
Unconventional light	602	21	20	12	16	124	0,11
Unconventional heavy coking	1335	42	155	58	17	160	0,12
Unconventional heavy hydrocracking	1468	45	155	54	17	160	0,12

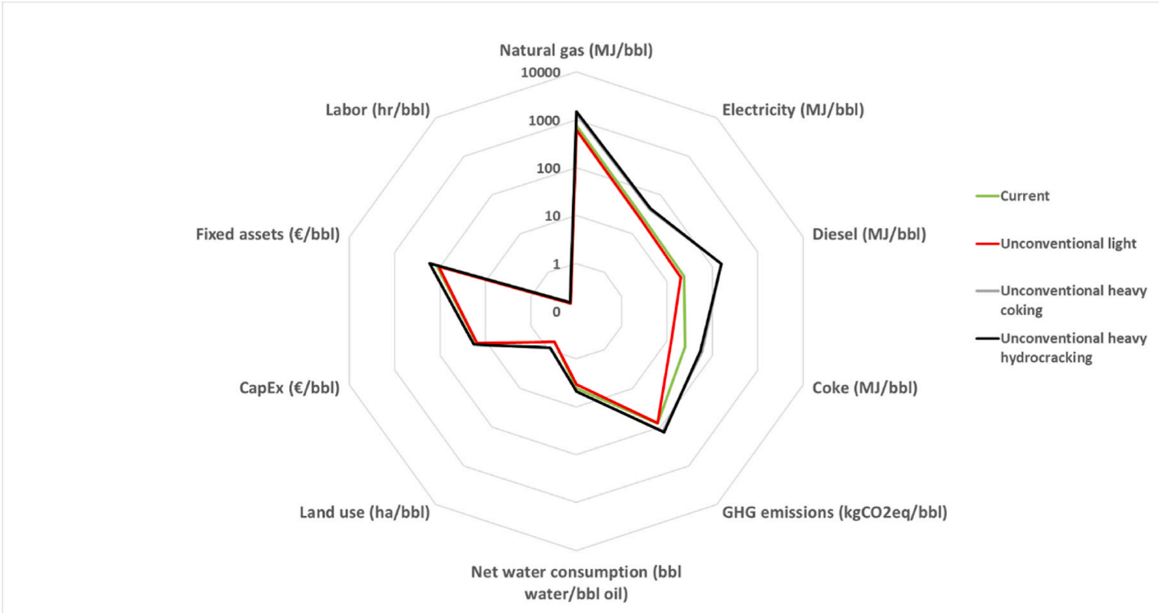

Fig. 2. Environmental, socio-economic, and technical pressures associated with the four selected production functions (logarithmic scale, intensive description per barrel of oil produced).

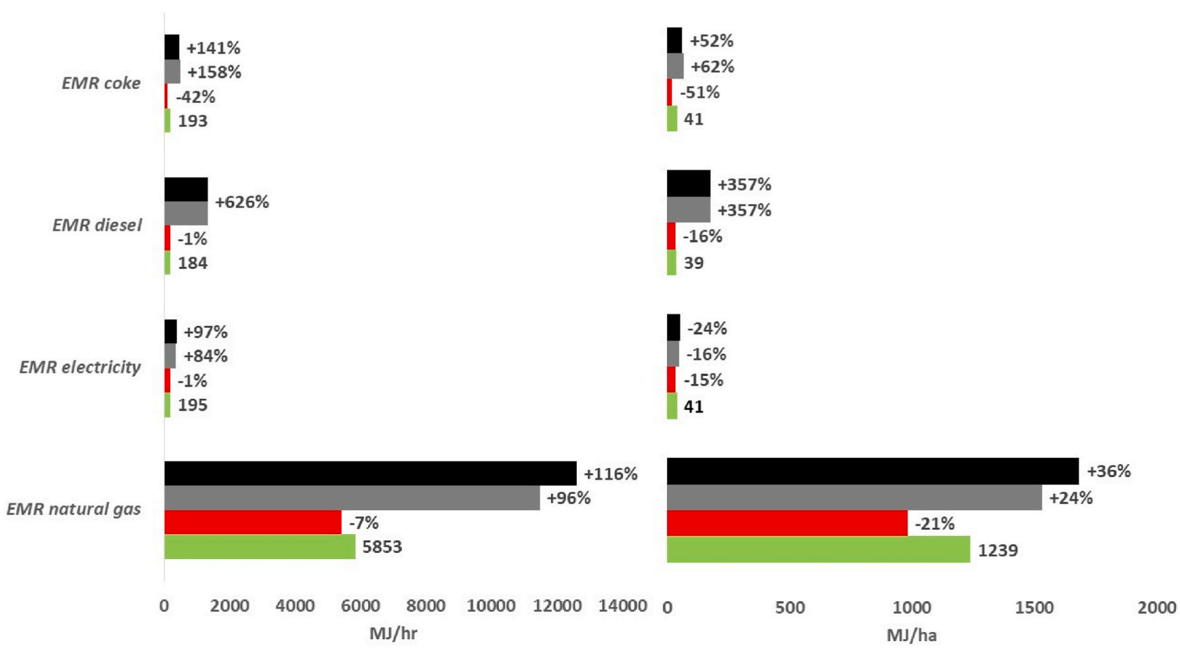

Fig. 3. Consumption of energy carriers per hour of labor (MJ/h) and per hectare of land (MJ/ha) for the four combined production functions (supply typologies). For color legend, see Fig. 2.

2. Check the actual impacts of the biophysical pressures in relation to feasibility and viability criteria (extensive)
3. Identify trade-offs among multiple dimensions (e.g., water, land, energy, labor, capital) in relation to policy claims (intensive and extensive)

For instance, Fig. 8 shows intensive and extensive benchmarks of labor requirements for different combined production functions (supply typologies). The intensive description in the upper part of the figure is typical of LCA and NEA. While useful to compare different supply chains, it gives only partial information about the actual performance of the system. The extensive description in the lower part of Fig. 8, on the other hand, simultaneously considers: (i) the combined production functions; (ii) the different societal requirements of oil products; (ii) the required size of the oil sector (i.e., application of the CF). This representation thus informs us about the actual pressure, in this case, on the anthroposphere. As shown for this specific example, even if the labor intensities per barrel of the unconventional heavy pathways are higher than that of the baseline, this is not necessarily also the case for the overall workload requirement. In fact, for the EU requirement pattern (but not the World and US patterns) the overall labor requirement of unconventional heavy pathways is the lowest. The same analysis has been done for several other dimensions (land, water, capital, etc., see Supplementary Material) and their combined use allows an assessment

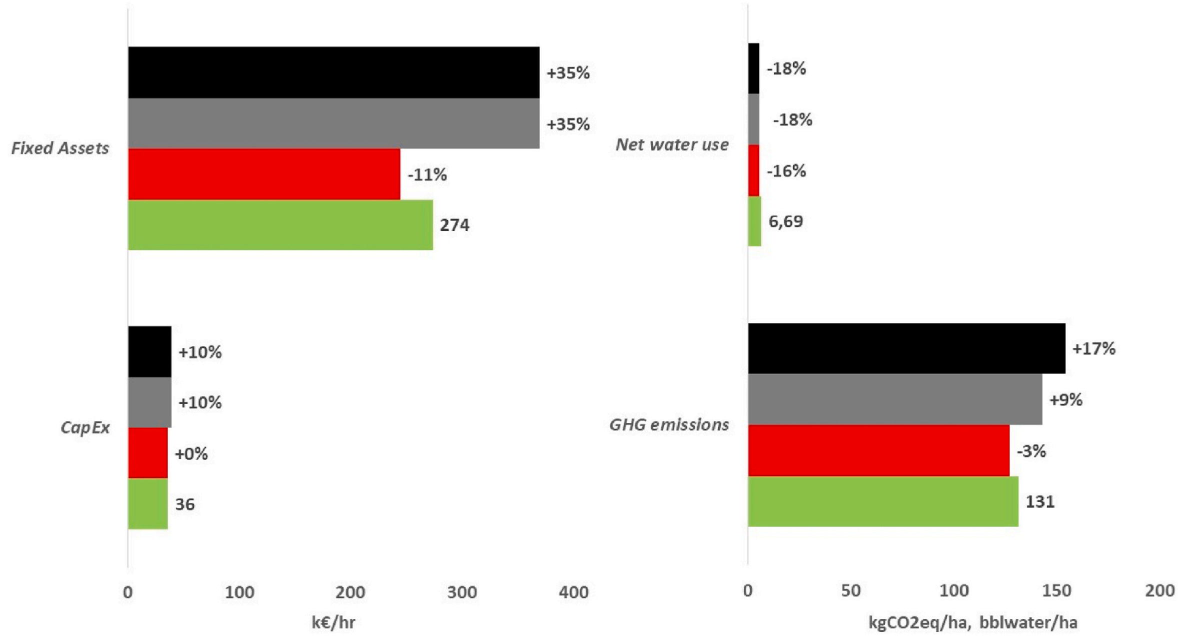

Fig. 4. CO_2 emissions and net water consumption per hectare (right), and fixed assets and capex per hour of labor (left) for the four combined production functions representing the supply typologies.

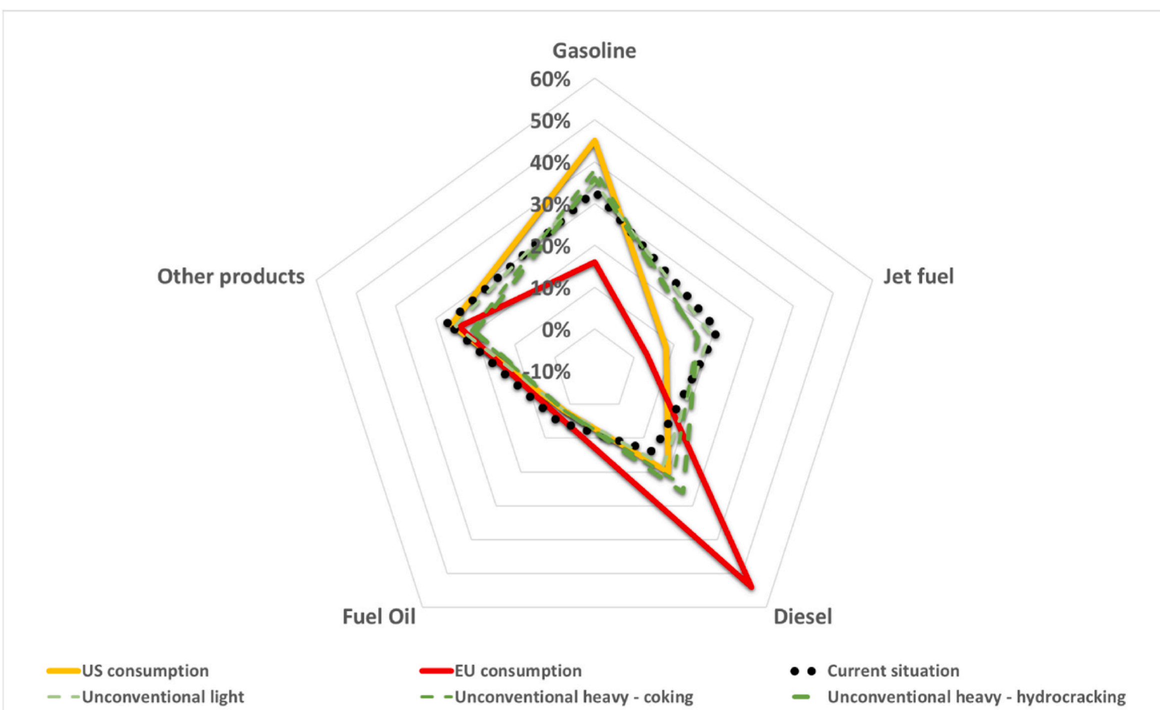

Fig. 5. Mismatches between net production and consumption of oil products across typologies of production and consumption patterns.

of trade-offs of policy choices, both on the production and consumption side. In this regard, it is relevant to recall that MuSIASEM is a semantically open accounting framework and therefore allows for the selection of relevant dimensions (attributes) by the users, thus encouraging an informed discussion among different agents.

The use of the Crack Limiting Flow (based on Liebig's law of limiting products), rather than the mere availability of primary energy sources, as an indicator of functional bottlenecks in the oil metabolism also represents an important step forward. The quality of the product slate refinable from different oil assays from around the globe in relation to the evolution of the oil product requirement [98] is a well-known issue from an economic [99] and a technical standpoint [100] (e.g., to increase petrochemicals and reduce gasoline and diesel). Traders and refiners optimize their *crack spreads*[1] in relation to: (i) the demand of oil

[1] From Wikipedia [131]: "***Crack spread*** *is a term used in the oil industry and futures trading for the differential between the price of crude oil and that of the petroleum products extracted from it. The spread approximates the profit margin that an oil refinery can expect to make by "cracking" the long-chain hydrocarbons of crude oil into useful shorter-chain petroleum products.*"

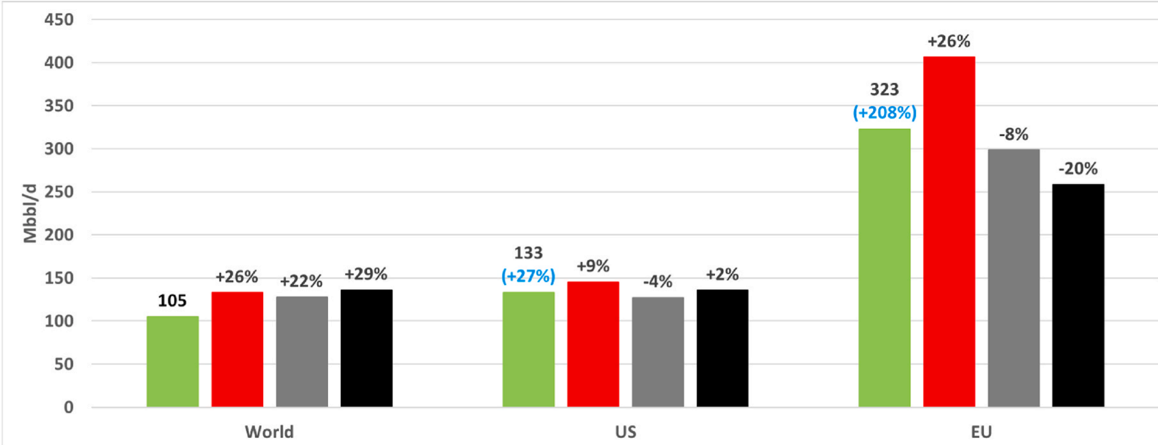

Fig. 6. Adjusted scale of the oil sector (daily production of barrels of crude) to meet CLF for the combinations of production and consumption typologies. Marginal increases in total supply (%) caused by different requirement profiles against the supply baseline are reported in light blue. Marginal increases (%) caused by changing the production function against the same requirement are reported in black.

Table 6
Coupling Factors and corresponding Crack Limiting Flows across production and consumption typologies.

	World		US		EU	
Current	1,00	–	1,27	Gasoline	3,08	Diesel
Unconventional light	1,26	Diesel	1,38	Gasoline/Diesel	3,87	Diesel
Unconventional heavy coking	1,22	Other products	1,21	Other products	2,84	Diesel
Unconventional heavy hydrocracking	1,29	Other products	1,29	Other products	2,46	Fuel oil

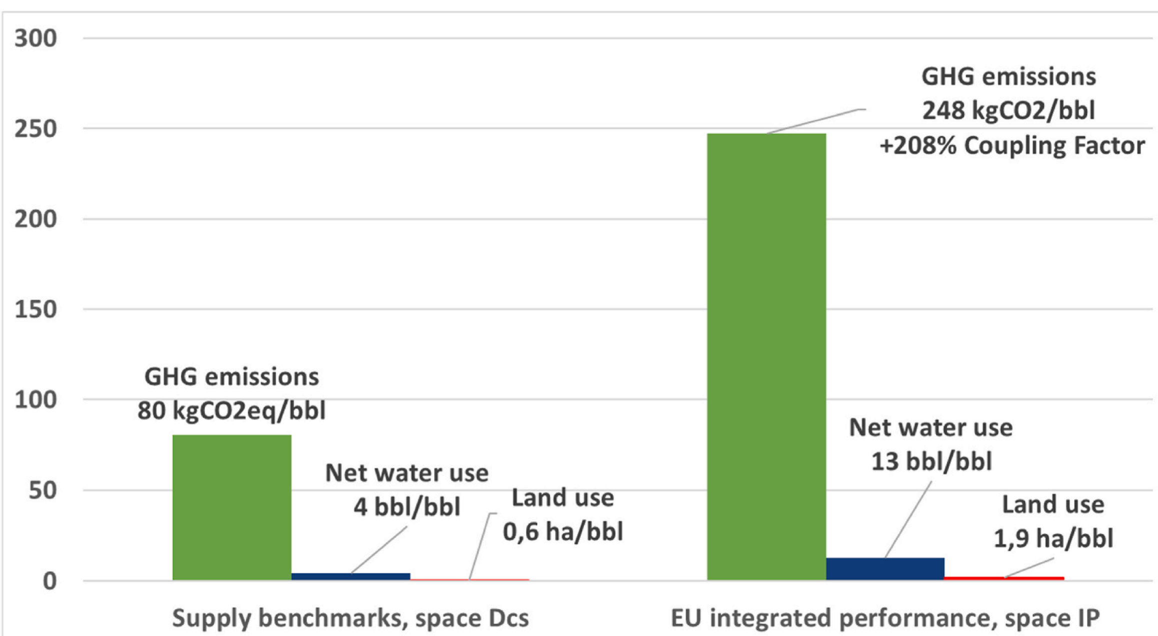

Fig. 7. Environmental performance of an EU demand-driven enlargement of the global oil sector (current production pattern), to match the requirement of diesel, compared to baseline performance (current consumption). See the Supplementary Material for the biophysical-technological (Fig. S17), environmental (Fig. S21) and socio-economic (Fig. S25) performance.

products from international markets; and (ii) the availability of different crude assays (WTI, Brent, medium or heavy Russian and Arabic oils). There is a general (but vague) understanding about the role of refiners in relation to decarbonization issues from a socio-technical perspective [101] and that of (shortages of) diesel in the current energy crisis [102]. However, there is a lack of scientific tools that bridge the quality of product slates (and related feedstocks) with societal consumption practices and assess the implications for the resulting biophysical performance. This work has attempted to fill this gap by providing a tool to operationalize the analysis of this issue and put it at the service of sustainability researchers.

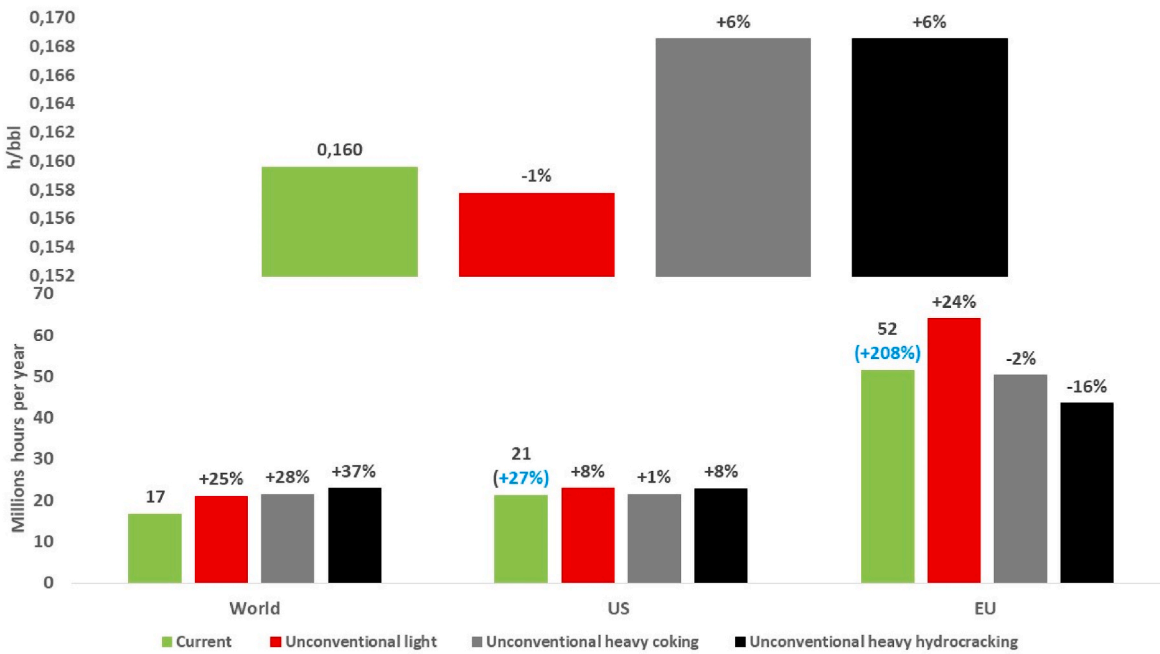

Fig. 8. Labor requirement per barrel (h/bbl) of the different combined production functions/supply typologies (fund, intensive description) (upper graph) and total hours of human labor (Mh/year) employed in the global oil sector (fund, extensive description) (lower graph).

4.2. Shortcomings of the proposed approach

In the current work, the methodology has been illustrated at the global scale for the sake of simplicity. We did not geo-localize oil exploitation nor consider trade of oil products among geographic regions. Several other studies on energy security have specifically and exclusively focused on import/export patterns and models aimed at representing those networks of trade flows [103,104]. However, in agreement with Baldwin [105] and Cherp and Jewell [75], we believe that a definition of energy security as securitization of imports *per se*, without relating these trade flows to the energy metabolic pattern at the national and global level, has limited value.

The metabolic benchmarks of the production functions (Table 1) represent internal and external *pressures*. This analysis should be complemented with geographical contextualization to assess the *impacts* on local ecosystems and societies. For instance, water and land requirements of unconventional oil exploitation may not be much of an issue in certain regions of the USA but can be in arid or densely populated areas. Trade among geographic regions may offset local shortages of oil products, as is evident from the better performance of the 'world' consumption pattern compared to either the US or EU consumption pattern.

In our analysis, we did not consider potential limits of extraction and refining capacity. This would require the integration of power capacity in the set of relevant attributes (dimensions) included in the analysis. Such limits may soon become relevant, notably for refining capacity, as companies are discouraged to invest in either exploration or refining capacity in the current political climate of low-carbon energy transitions and 'peak oil demand' [106,107]. Refineries are expensive, requiring investments with long pay-back periods, and if we expect a continuous change in both the crude slate (input) and required product slate (output) we should consider the need of continuously upgrading the global refinery system. For instance, tight oil may soon face bottlenecks in refining conversion capacity [22]: "US refining system approximately hits the 'refinery wall' at 40% light tight oil on the total capacity". This capacity limit will be lower at the global level given that the global refining system on average is designed to operate at full capacity with a high supply of medium to heavy oils. Hence, refiners worldwide might not be able to absorb the +26% additional supply linked to a transition to unconventional light pathways (Table 6, Fig. 6). In addition, high shares of light (tight) oil in the supply mix narrow down refiners' margins [108]. Note that at present, global fossil fuel subsidies are still high – estimated by the International Monetary Fund (IMF) at about US$6 trillion in 2021 [109], of which the larger share comes from ""under--charging" for the environmental costs associated with the fuels. This may change in the near future.

A last, but important drawback of our approach is that it requires extensive and complex sets of raw data. These data are not always readily (publicly) available and require the use of multiple data sources that, more often than not, use different protocols. This implies that the analyst will have to handle different taxonomies and accounting methodologies. For instance, in the current study, consumption data are from both the Eurostat and EIA databases, which implement different oil product taxonomies (see supplementary data, section S3.1 and S3.2, for the mapping relations). On the production side, data were derived from Ref. [24], which reports only aggregate categories, hence more detailed assessments of specific oil cuts (e.g., petrochemicals, that comprise a relevant and increasing share of refinery products) are difficult to execute. A uniform protocol for taxonomies and accounting rules is urgently needed if we are to coherently assess societal energy metabolism from PES to energy services [110].

4.3. Policy relevance

In spite of the drawbacks of our approach, we believe that the metabolic perspective offers several entry points for policy making in the domain of energy security. Indeed, solutions for decarbonization should not only be sought by advocating more technological innovation, new business models or selectively discouraging the consumption of individual emission-intensive oil products [57,101,111,112]. Instead, we should analyze this issue by considering fuel production and consumption as an integral part of the functioning of society [113].

At the global scale, any stable metabolic state entails that supply and requirement patterns of oil products must match in the long term. The currently unbalanced requirements of diesel and gasoline in, respectively, the EU and USA in relation to the global product slate can only be maintained because non-limiting, low-quality products (e.g., heavy fuel oils and coke) are exported to and used in countries with looser environmental regulations. For instance, China has seen an increase in the import and use of petcoke in response to the increase in unconventional heavy oil refining in the USA and Canada [114]. Simply meeting either the US or EU oil product consumption pattern at a global scale would be impossible without significantly increasing the daily global production. In the case of the EU, this would require triplicating the current production (+208% marginal increase, up to 323 million bbl/day, see Fig. 7), which is clearly an implausible option. Hence, the EU would have to push for developing unconventional heavy oils and/or significantly reduce diesel consumption. On the other hand, for the USA it would be advisable to reduce gasoline requirements and maintain a high refining capacity for light products (i.e., gasoline and naphtha).

Diesel is undoubtedly the most critical fuel in matching oil product supply with requirements. It has a crucial role in industry and heavy transport and represents a staple in the industrialization of developing countries. In addition, current international climate policies, requiring relatively clean fuels and compliance with energy efficiency standards, are likely to further push diesel demand in countries like China and India. While diesel is easily distillated from medium and heavy (cheaper) oils without deep refining, tight oil, the most promising unconventional light resource, with metabolic benchmarks comparable to conventional resources, cannot provide a large share of middle distillates. Indeed, diesel is consistently the crack limiting flow in the unconventional light supply pattern (Table 6). It follows that if we go down the path of unconventional light oils, solely meeting current diesel demand would already imply an increase in overall supply (+26% with the current global consumption pattern, +36% and +234% respectively with US and EU requirement patterns, see Fig. 6) and associated biophysical pressures (Fig. S18). Extensive exploitation of unconventional heavy pathways, with a relative higher diesel supply, would reduce the total supply required to meet current demand patterns, but not necessarily the associated biophysical pressures because diesel production in these pathways is inefficient (Tables S12–S13). For instance, total GHG emissions would increase for all the requirement patterns considered (Fig. S11). In this regard, it is important to observe that the current policy line of applying carbon taxes ("smart tax") on carbon intensive oils [56,112,115] considers only one dimension of performance (GHG emission). Consequently, exploitation of heavy oils is discouraged due to their carbon intensity [116] and the oil sector is increasingly being pushed toward reliance on (aging) conventional oil – which is gradually becoming more emission intensive [94] and more impacting on the environment in general [117] – and unconventional light crudes (tight oil), while the transition to a low carbon energy matrix based on renewable sources is expected to take shape [115].

Broadening the discussion beyond the oil sector, substitution of biofuels, green hydrogen and ammonia for diesel – for instance as pursued by IMO [118] – and fossil fuels in general, is unlikely to materialize in the near future. Thus far, the experience with biofuels has been negative [119] and the production of alternative synthetic fuels is still in a stage of low technological readiness. Electric vehicles – expectedly powered by solar and wind in the future [120] – are expected to reduce gasoline consumption in the USA and diesel in the EU. However, their large-scale implementation is still questionable due to lack of storage needed for scaling up the supply of intermittent sources of electricity to the grid [121] and lack of materials for the batteries of a new fleet of electric vehicles [122]. Moreover, modern societies will still need heavy oil products for industrial and agricultural inputs as well as light distillates and plastic for the functioning of the economy: the use of petrochemicals is ubiquitous and growing [123]. As we have shown, unconventional light pathways cannot even meet their own internal coke requirement (Table 2), while increased exploitation of unconventional heavy oils (to sustain diesel production), could face bottlenecks of light petrochemicals.

5. Conclusions

We have shown that the energy security of a complex society cannot be captured at a single scale of analysis (primary energy source exploitation) or by a single dimension of performance (GHG emission). Reducing a complex issue, as is the sustainability of the societal energy metabolism, into a simplistic representation of a technical issue by adopting a linear product-centered approach is a crucial flaw [124]. The metabolic perspective on energy security, illustrated in this paper, overcomes this limitation by considering the compatibility of the contingent metabolic pattern of demand and supply of oil products – the admissible set of relations over primary energy sources, energy carriers and end uses of a given society – with external (feasibility) and internal (viability) constraints. In our approach, admissible metabolic states are defined by two main drivers: (i) the desired societal energy end uses and the corresponding requirement of specific oil products (desirability) and (ii) the realizable production functions, their corresponding product slates and multi-dimensional integrated performance space (their pressures on the economy and the environment). The reverse of the medal is the amount and detail of the data required for carrying out the analysis.

We demonstrated that, at the global level, the flexibility in the output of oil products, given by the feasible and viable sequential supply pathways, is low. This constraint may become more pronounced in the near future because of potential bottlenecks in the oil extraction and refining capacity. Adjusting consumption patterns (desirability) will therefore be increasingly important for the sustainability of oil metabolism rather than optimizing the supply side (viability, feasibility). However, changing consumption patterns means changing social practices [70,125], and this implies a difficult 'lock in' to overcome [126,127]. How the societal consumption pattern of oil products relates to end uses is therefore an important field for future work in relation to decarbonization pathways and energy security.

The illustration of our approach at the global level did not consider trade of primary energy sources and energy carriers and hence did not assess the sustainability criteria of openness. The oil metabolism at the national level is characterized by extreme openness, and hence the performance space related to the viability and feasibility criteria would better be geo-localized to account for the externalization of economic and environmental pressures. This is a priority in the further development of our approach.

Responsible energy policies should consider the oil sector as an integral part of society, and oil products not as independent elements, but as product slates jointly produced to meet societal requirement for energy carriers. Labeling specific oil products as relatively clean or dirty *per se* (in an attempt to find "optimal limits" of CO_2 emissions and other solutions adopting a narrow option space [128–130]) distracts from the main concern of how to reduce overall oil consumption. There is no such thing as a good or bad primary energy source or energy carrier, only sustainable or unsustainable societal metabolic patterns. At the end of the day, the deliberation over which metabolic pattern we want to pursue is a social, political, and cultural process, and not a purely technical one.

Credit author statement

Michele Manfroni: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Sandra G.F. Bukkens: Formal analysis, Writing – review & editing. Mario Giampietro: Writing – review & editing, Supervision

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.

Data availability

Data will be made available on request.

Acknowledgements

Michele Manfroni gratefully acknowledges financial support from the Catalan administration/AGAUR (Grant number: 2018 FI_B 00313). The Institute of Environmental Science and Technology (ICTA) has received financial support from the Spanish Ministry of Science, Innovation and Universities, through the "María de Maeztu" program for Units of Excellence (CEX2019-000940-M). Michele Manfroni wants also to thank Dr. Henrik Wachtmeister for his precious insights. This work reflects the authors' view only; the funding agencies cannot be held responsible for any use that may be made of the information it contains.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.125256.

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