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The energy metabolism of post-industrial economies. A framework to account for externalization across scales

M. Ripa [a,*], L.J. Di Felice [a], M. Giampietro [a,b]

[a] Institute of Environmental Science and Technology (ICTA), Autonomous University of Barcelona (UAB), 08193, Bellaterra, Spain
[b] ICREA, Pg. Lluís Companys 23, 08010, Barcelona, Spain

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ABSTRACT

Post-industrial societies heavily rely on the consumption of embodied energy for their activities – i.e., energy invested elsewhere to produce what is imported and consumed (or re-exported). The openness of the energy sector poses modelling challenges, calling for multi-scale, integrated analytical frames. We propose a methodology grounded in societal metabolism aimed at analysing the behaviour of a system (where the system may be a region, a country, a continent, etc.). We make the distinction between three types of scales necessary to contextualize the behaviour of the energy sector within a globalized economy: the macroscope, the mesoscope and the microscope. The methodology is applied to analyze the energy sector of EU19 countries, considering internal and external labour, primary energy sources, energy carriers and GHG emissions. The results show that imported primary energy sources and energy carriers within the EU19 are associated with externalized pressures and impacts. For example, accounting for the externalized carbon emissions of the energy sector raises total GHG emissions of the sector by 60% on EU average. This has implications for the assessment of the effectiveness of global sustainability policies. By not accounting for externalized effects, energy models can miss relevant information about the interactions among systems.

1. Introduction

In post-industrial societies the domestication of energy, i.e. the evolution of the original 'control of fire', followed three major stages. In the first stage, human survival depended on biomass, a form of energetic *income* provided for free by natural processes. This supply of energy input was circular and sustainable. Yet, it was dispersed and difficult to convert into useful power: its exploitation entailed a low return on human efforts [1]. The second stage began about 150 years ago with the use of coal and steam engines. With the industrial revolution, living standards (and hence levels of consumption) rose above the limit allowed by the energetic income provided by biomass. Societies achieved this result by depleting a form of energetic *capital*, i.e. the stocks of fossil energy available on the planet. The transition from traditional sources of biomass that dominated up to the end of the XIX century to the reliance on fossil energy in the industrial revolution, from the 1890s to the 1950s, allowed for dramatic changes in technology. Within less than a century, societies who had previously operated solely on land-based fuels, characterized by a low power density and high labour requirements, were able to use large quantities of high-quality fossil energy stocks, requiring negligible quantities of land and labour for their exploitation (see Table 1).

A third stage in the evolution of the control of energy, called post-industrial revolution [2,3], introduced embodied energy, i.e. the energy embodied in the production of imported goods and services, among the possible energetic inputs to use [4]. This allowed post-industrial societies (only a part of the whole humankind) to undergo a process of tertiarization, whereby most resources, including human labour, are invested and/or consumed in the tertiary sector of the economy, which is also associated with the highest Gross Value Added (GVA). This change has been increasingly driven by a ballooning finance sector [5]. As a result, post-industrial societies can use and control more energy than industrial ones did previously, by consuming energy both directly and indirectly, through energy embodied in trade. The accounting of these chains of direct and indirect energy consumption is relevant for global sustainability policies, as only considering what happens within a country's borders does not reflect the

* Corresponding author.
E-mail address: maddalena.ripa@gmail.com (M. Ripa).

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interconnected nature of modern energy systems.

The externalization of some functions (e.g., the supply capacity of commodities or the environmental sink capacity) to other economies can alter the requirement of energy and other material flows for the operation of a given economy. This concept was introduced in the early 1960s by Georg Borgström under the label of ‘ghost acreage’. Ghost acreage, later renamed ‘embedded’ or ‘virtual’ land or ‘land footprint’, is “the computed, non-visible acreage which a country would require as a supplement to its present visible agricultural acreage in the form of tilled land in order to be able to feed itself”[6], p. 71]. Similarly, Catton (1980) referred to the concept of “phantom carrying capacity” [7].

More recently, the concept of externalization has been called into play to highlight the potential drawbacks related to some policy-induced changes that, without taking into account all the indirect consumption and impacts caused outside country’s borders, may eventually lead to the so-called carbon leakage phenomenon [8–10] and/or to relative or virtual decoupling (i.e. the observed decoupling in some Western countries is virtual because largely due to outsourcing of energy intensive activities) [11,12]. Therefore, while, on one hand, externalization has been framed as a thorny aspect to be considered in policy-making, on the other hand, the issue of externalization has been also related to the theory of ecologically unequal exchange and its relevance for global environmental injustice [13,14].

In this paper, we define externalization as *the set of entangled social, economic and environmental effects stemming from the displacement of extractive and productive industries outside of governance boundaries (which may be regional, national or supranational).* In other terms, externalization refers to the investment of resources and production of environmental impacts taking place outside of a reference system, associated with goods and services consumed within the reference system. This includes, for example, labour invested elsewhere to extract the primary energy sources consumed within the system, or the greenhouse gas (GHG) emissions associated with the manufacturing of imported goods. In our EU case study, we focus on the externalization of labour, primary energy sources, energy carriers and GHG emissions associated with the energy sector.

In conceptual terms, we frame externalization within a metabolic view of socio-economic systems [15–17]. In this view, these externalized variables are not just connected to the reference system, but form part of a larger, interconnected dynamic, whereby resources invested in a certain sector (e.g., labour invested in agriculture for exports) constrain how many resources are available in other sectors (e.g., labour available for services). As acknowledged by Giampietro et al. (2012) [18], the process of post-industrialization of modern societies simultaneously relies on and strengthens two relationships. First, primary sectors of the economy (i.e. agriculture, energy and mining, manufacturing) use only a tiny fraction of the work force, with high labour productivity and large energy throughputs. Second, goods, services and capital are imported to cover the gap between what is consumed and what is domestically produced. A strategic organization of the global economy based on transnational corporations can ensure that the required flows of goods and products are available to post-industrial economies even when the required resources, technical capital and labour needed for their production are not invested within national borders. From a societal metabolism perspective [18–21], embodied energy is not only a flow that is traded among systems but it is also associated with other dimensions (most importantly, labour) which affect the metabolic behaviour of both the importing and the exporting system.

Analyzing this role of externalization in the metabolic pattern of societies requires the adoption of a multi-scale approach, grounded in complexity [22–24]. Across different scales we can ‘see’ certain pieces of information, but only because the decision of focusing on a given scale entails missing other pieces of information available at other scales. Every time a system is observed, modeled and measured, we are defining an abstraction that is associated with a specific perception of a particular portion of the external world [22,25]. In practice, in discussing and quantifying externalization from a metabolic perspective, we identify three scales relevant to the assessment of externalization. The *macroscope* is the description of the overall metabolic pattern of a society. It contains the relations over the set of the economic sectors of society, which we refer to as *constituent components*. The *mesoscope* determines the level of openness of the system, i.e. the interaction of the system with its environment. At the *microscope*, we study the mix of production processes taking place inside and outside the economy, by defining a set of functional and structural elements inside the constituent components.

The aim of this paper is twofold: first, to illustrate a multi-scale methodology developed within the EU MAGIC project [26] that can be used to describe the metabolism of systems and the associated implications for the processes taking place both in the technosphere and the biosphere. Second, to apply this multi-scale analysis to quantify the externalization (of energy, labour and environmental pressures) of the energy sector in EU19 countries.

The remainder of the paper is organized as follows. Section 2 presents the conceptual building blocks of the methodology, focusing on three scales of analysis. Section 3 presents the results obtained by applying the methodology to the analysis of the performance of the energy sector of EU19 countries. Section 4 summarizes our main contributions and limitations, both methodological and in relation to the case study.

2. The multi-scale assessment of metabolic patterns

2.1. The conventional set of indicators for energy policy

Many indicators such as energy intensity, net-import dependency, and energy per capita have been proposed by governmental institutions and agencies to guide energy policies [27–29]. However, these indicators are based on assessments of direct energy use, which cannot fully describe the overall energy consumption associated with the production and use of imports. Since countries in a highly globalized world are increasingly involved in international trade, some scholars argue that the EU’s share in meeting global demand for goods is shrinking and gradually (or rapidly, in some cases) being replaced by new capacity in China or elsewhere in the world [30–32]. If countries can meet their emissions and/or energy targets by outsourcing carbon intensive production, this strategy may seriously undermine the efficiency of global policies [33].The most common analytical tools to quantify energy (and other elements) embodied in trade are footprint-type methods including life cycle assessments (LCAs) [34] and input/output (I–O) analyses [35–37]. Footprint approaches (such as LCAs, water footprints or Emergy analyses) adopt a microscale perspective, modelling technical coefficients for particular products using data and technical information on all upstream production processes in the supply chain. Conversely, I–O models adopt a macroscale approach whereby coefficients are modeled starting from statistical data at the macro level for broad product groups or sectors.

LCAs are mostly used to assess the embodied carbon, water and energy of single processes [38–42], but the methodology is rarely scaled up to assess the embodied energy of an entire sector and or/ economy, although some progress has been made recently by means of hybrid LCA approaches, such as Environmentally-Extended Economic Input-Output Life Cycle Assessment [43]. On the other hand, I—O approaches (and their variants, Multi-Region I—Os and Single-Region I—Os) have been mainly employed to calculate the embodied energy consumption of entire sectors [44,45] and international trade [10,30,31,46—49].

These approaches, as any other method, have their limitations. For example, while LCA results can be easily used to check whether or not it is reasonable to produce a certain fuel by assessing whether the energy in the end product is larger than the energy used along the life cycle, the use of energy indicators (such as energy demand, fossil energy use, etc.) is very often poorly described and motivated [50]. Whether or not renewable energy is included, or energy consumption is intended for energy and/or material purposes, or whether the energy is assessed as primary energy or secondary energy, is often lacking of clarity [50]. For example, in considering the embodied energy consumed in production, there is no way to clearly discriminate between the primary energy sources (crude oil, natural gas, coal, etc.), being depleted from the biosphere, and secondary energy sources, or energy carriers (electricity, heat and fuels), consumed by end-users [50]. This aspect becomes relevant if an assessment aims at responding to concerns over the limited availability of local or global energy reserves and to constraints posed by the consumption of resources across different economic sectors [51].

I—Os, on the other hand, aggregate products with different physical characteristics into product groups using a common unit of economic value (what is known as sector-level aggregation). This is not suitable for assessing energy consumption and its associated environmental pressures, since sub-sectors contained within the same aggregate I—O sector may exhibit highly different carbon and/or energy multipliers. This is especially true if the disaggregated sectors are heterogeneous with respect to their economic and environmental characteristics [52,53].

With regards to using these approaches to assess the impacts of externalization, neither LCAs nor I—Os include concepts of embodied primary energy sources or embodied energy carriers (such as embodied coal, oil or nuclear electricity). These represent a specific type of energy consumed directly and indirectly in products or services. Cross-country comparisons are also sensitive to choices of the energy accounting framework. In this case, the two approaches, very often run in parallel, provide important pieces of information at different scales. What we propose is a methodology that can bridge different pieces together, as to better understand the system under analysis and to provide a more comprehensive view on countries' metabolism. To do this, disaggregation is required across scales, across types of energy (primary vs. secondary), and across nexus elements.

2.2. Sustainability across scales

The methodology presented here is a development of the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) [17]. MuSIASEM has three aims. The first is to establish a bridge between quantitative information characterizing the internal state associated with the metabolic pattern of societies and the pressures that the metabolic pattern exerts on its embedding ecosystems. The second aim is to describe the characteristics of the metabolic pattern, looking at the economic sectors of the system (what we also refer to as 'constituent components') across different levels of organization. The third goal is to define the degree of openness of the social-ecological system, analyzing exchanges with other systems.

The quantitative characterization of these different aspects requires the adoption of different space-time scales and different dimensions of analysis [18,23]. Many non-equivalent abstractions of multi-scale systems can be generated. These potential abstractions "are all present in the original [hierarchical] system", but "which one we actually 'see' is specified entirely by how we choose to interact with the system" [54]. What we see when observing (the perception that will be represented) depends not only on the nature of what is observed (e.g., the physical shape of the observed system) but also on the choice of how to observe it (the method of observation) [23].

In relation to this epistemological challenge, the proposed methodology uses three different abstractions to generate an integrated set of representations of the metabolic pattern of socio-economic systems:

1. The *macroscope*. Looking at the whole metabolic process taking place in society, the dynamic equilibrium between *production* and *consumption,* an emergent property of the whole, is considered. Using this abstraction, it is possible to establish a bridge between the biophysical and the economic dimensions of analysis, focusing on the relations between the parts (the economic sectors) and the whole (society).

2. The *mesoscope*. Looking at the degree of openness of the metabolic pattern of a given society, the information obtained by the mesoscope allows studying the effects that trade has both inside and outside the system. Whenever consumption is larger than local supply, we can calculate the size of 'virtual supply systems' that are needed to produce the imported inputs. Here, the exports of the system under analysis are not detracted from the balance. Instead, they are considered to be inputs into an economic sector, since they entail the exchange of energy products for GVA (Gross Value Added).

3. The *microscope*. Looking at the biophysical processes taking place inside (or outside) the boundaries of the system, at the local level we study the technical coefficients of the physical processes of production - e.g. the operation of a power plant - in quantitative terms. By using the microscope, we can describe the relation between technologies and their environmental pressures.

The next sections (2.3, 2.4 and 2.5) explain the three different scales of analysis in more detail.

2.3. The macroscope: Studying how the interaction across economic sectors maintains the identity of the system

Economic sectors, i.e. the constituent components of the system, depend on each other for their metabolic activity [55,56]. They produce and consume, in an integrated way, different types of secondary inputs and outputs [18]. The macroscope can be used to study the relation between any one of the constituent components and the others within the set of relations determining the emergent property of the whole. Fig. 1 shows a representation of the metabolic pattern based on five constituent components making up society (i.e. the internal - referred to the system under study - technosphere embedded into the biosphere). The five constituent components (i.e. end-users accomplishing a specific societal task), shown as hexagons, can be divided into two groups. The first group is the dissipative part, including four economic sectors that are consuming energy carriers: the *household sector*, with the function of reproducing humans; the *services and transport sector*, with the function of reproducing institutions and guaranteeing citizen well-being; the *industrial sector*, with the function of producing goods, technical capital and infrastructure; the *agriculture sector*, with the function of producing food and fiber. The second group is what is known as the 'hypercyclic' part, made up by the only sector that generates more energy carriers than it consumes, i.e. the energy sector. In the hypercyclic part, the energy sector upgrades natural resources from their raw state (as they are in the biosphere) into

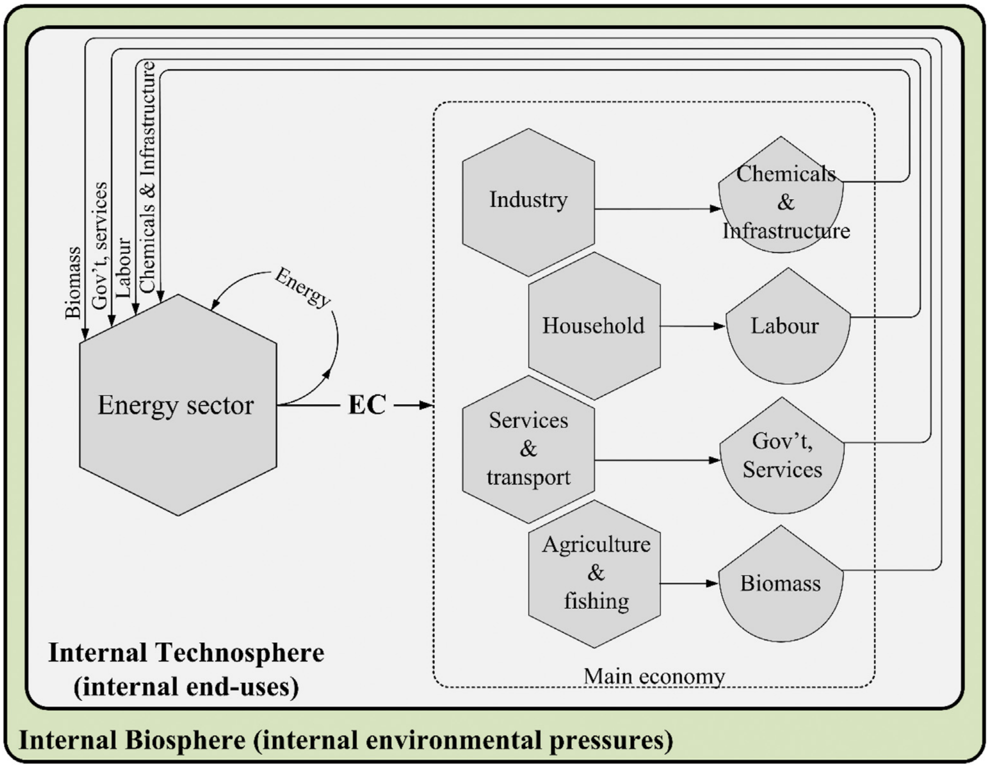


Fig. 1. The energy sector supplying and consuming matter/energy/services in society, seen through the macroscope.

'useful' energy forms (in an anthropocentric perspective), by means of exosomatic energy converters. We refer to the natural resources as primary energy sources (PES) and to the useful energy forms as the energy carriers (ECs) that are needed to maintain and sustain the whole social system [57,58]. To do so, the energy sector metabolizes materials, labour and a part of its own output of energy carriers. On the other hand, other economic sectors supply the energy sector with services, chemicals, labour, etc. (represented by drops/stocks in the figure).

2.4. The mesoscope: Assessing the implications of externalization

When importing goods, societies do not only indirectly use natural resources (land, water, soil, biodiversity) but also social and economic resources, such as technology and hours of labour. To address this, the proposed methodology adopts a conceptual tool developed in relational analysis, called the *metabolic processor* [19,59,60] allowing for the simultaneous representation of flows

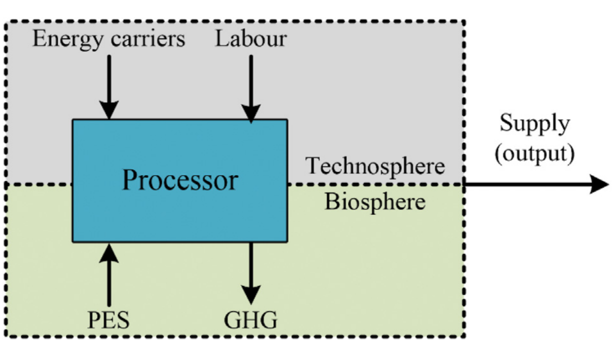


Fig. 2. The double interface generated by the metabolic processor.

relevant for socio-economic analysis and environmental impact analysis. A simplified metabolic processor (Fig. 2) identifies an expected set of relations regarding: (i) a structured process capable of producing a given output or expressing a given function; (ii) a profile of inputs and outputs in both the technosphere and the biosphere required for that purpose.

Using the terminology proposed by Georgescu-Roegen [18,61] the input flows can be divided into flow-inputs from the technosphere (e.g. energy carriers) and fund-inputs (e.g. labour), as shown in Fig. 2. Primary flows and funds, shown at the bottom of the figure, are exchanged with the biosphere: in this example, primary energy sources (PES) are on the supply side, and GHG emissions are on the sink side.

In the case of trade, imports into the energy sector can take two different forms: primary energy sources, entailing the externalization of environmental pressures (e.g. fossil stocks depletion) to other social-ecological systems, or energy carriers (such as electricity, fuels and gas), entailing not only the externalization of environmental pressures, but also the consumption of secondary inputs.

Therefore, in order to be able to identify the level of openness of the metabolic pattern of a social-ecological system, using available statistical data, we have to identify and quantify the flows using categories of accounting that are different from the ones used in the macroscope. In the macroscope we used typologies of 'energy carriers', while in the mesoscope we use typologies of 'energy commodities'. In the macroscope, we make the distinction between types of energy carriers (e.g. electricity, heat and fuels) and primary energy sources (e.g., coal or oil). In the mesoscope, energy commodities make the additional distinction on where PES and EC are produced: local/internal PES used for local EC; imported PES used for local EC; imported EC. Using this distinction, we can calculate four different sets of data useful for characterizing the metabolic pattern according to the four matrices shown in Fig. 3. Two axes -

one referring to the 'sphere' (biosphere or technosphere) and another one referring to the 'placement' (internal or external) - divide the plane into four quadrants of information:

1. *Internal End-Use matrix* (EUM_{INT}), focusing on the consumption of ECs used ***inside*** society (local consumption), including exports as an economic sector;
2. *Internal Environmental Pressure Matrix* (EPM_{INT}), focusing on the primary flows exchanged with the biosphere ***inside*** the system's border (local environmental pressures);
3. *External End-Use matrix* (EUM_{EXT}), focusing on the consumption of secondary inputs used in the technosphere to produce imports ***outside*** the border of the system (externalized consumption);
4. *External Environmental Pressure Matrix* (EPM_{EXT}), focusing on the primary flows exchanged with the biosphere to produce imports ***outside*** the border of the system (externalized environmental pressures)

2.5. The microscope: Assessing the local environmental impacts associated with production

At the level of the microscope, we focus on relationships between processors and their embedding environments. Fig. 4 shows a specific set of relations over structural and functional elements of the metabolic network described as processors. Rectangles represent processors, drops represent fossil stocks and circles depict the flows of either primary energy sources and energy carriers that can be locally supplied, imported and exported. At this level we introduce a third metric to account for energy flows, i.e. 'energy transformations'. This is needed to identify the specific relation between inputs and outputs at the local level. For example, the supply system of electricity can be realized by different mixes of power plants – e.g. coal, nuclear, wind. Thus, in order to specify the exact relations between the supply of electricity and the requirement of primary energy sources, labour and the internal consumption of other secondary inputs, we have to specify the mix of local processes associated with this supply.

The degree of detail at this level allows for a site-specific location of environmental pressures and, therefore, a definition of the environmental impacts. When working with specific geolocations, we can compare environmental pressures with the characteristics of the local ecological funds and/or resources stocks.

3. An application to the analysis of the energy sector of EU countries

This section shows the results of an application of the proposed methodology to 19 member states (listed in Table 1) of the European Union (EU19) for the year 2016. The results are organized following the three scales (macro, meso and micro) introduced above, and referring to the four matrices of information (internal and external end-use matrix, internal and external environmental pressure matrix).

3.1. Material and methods

Building on the concept of virtual and embodied imports [62,63], we refer to externalized energy commodities as those directly imported (both primary energy sources and energy carriers) and those embodied in the direct energy imports (e.g. electricity needed to extract coal, or coal needed to produce the electricity that is imported). All the results are shown on a per capita basis, for comparability. Population data are taken from Eurostat [64]. Detailed methods and data sources are provided in the Supplementary Material (SM), where the case of mapping data is also addressed.

3.1.1. End-Use Matrix (EUM) data sources

3.1.1.1. Energy Carriers & Labour in EUM_{INT}. The throughputs of energy carriers (electricity, heat and fuels) consumed in different

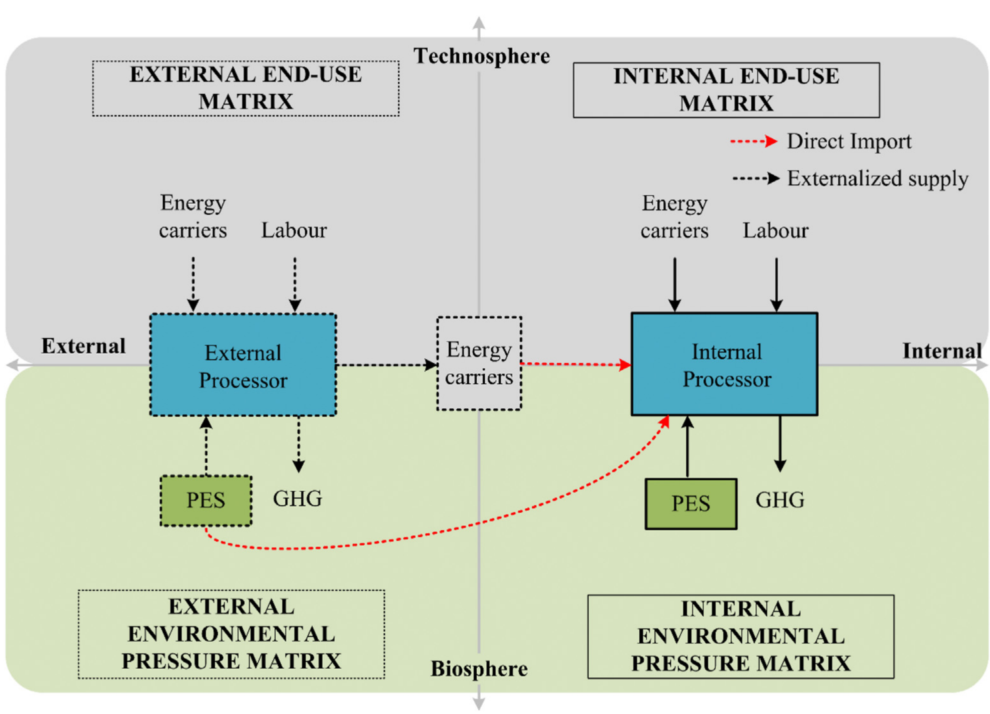


Fig. 3. The four matrices at the mesoscope level of analysis.

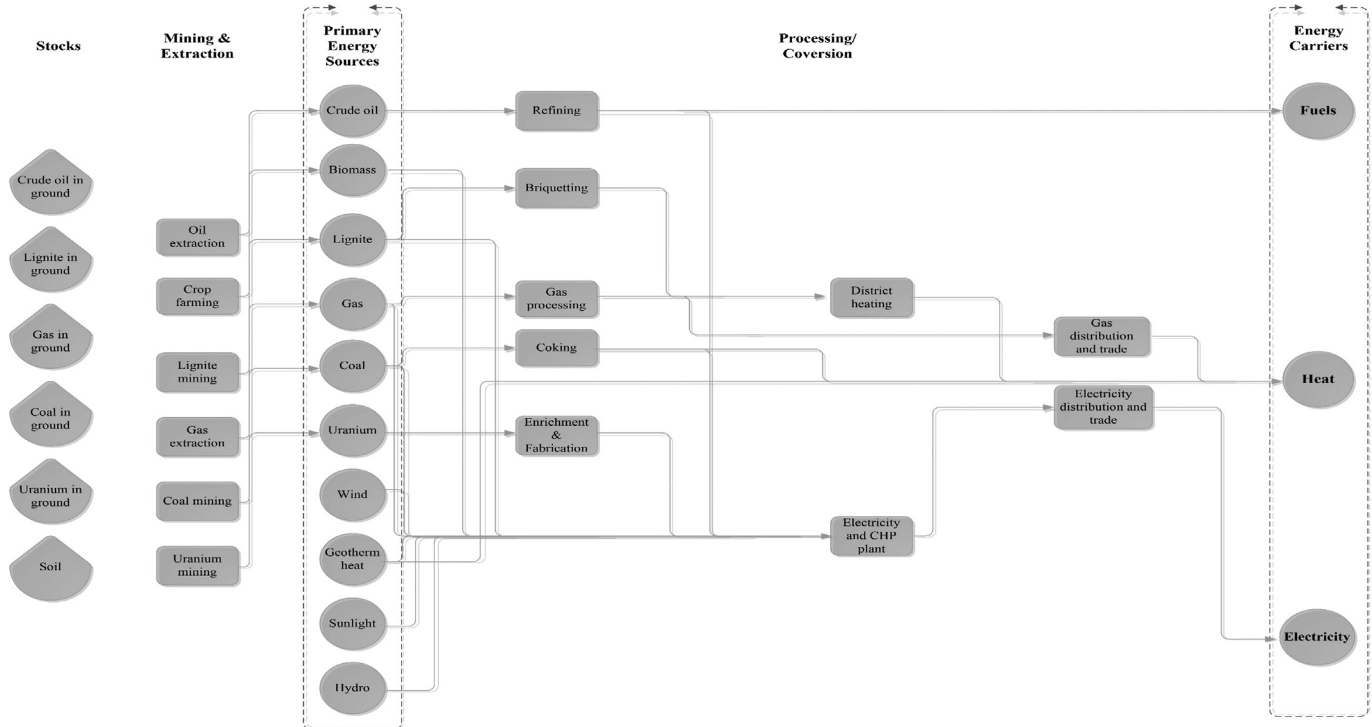


Fig. 4. Relations among processors.

Table 1
Selected countries for the analysis.

Abbreviation	Country name
AT	Austria
BE	Belgium
CZ	Czechia
DK	Denmark
FI	Finland
FR	France
DE	Germany
EL	Greece
HU	Hungary
IE	Ireland
IT	Italy
LU	Luxembourg
NL	Netherlands
PL	Poland
PT	Portugal
SK	Slovakia
ES	Spain
SE	Sweden
UK	United Kingdom

economic sectors, as well as in energy processes, were obtained by aggregating the energy commodities provided in the Eurostat Energy Balances [65]. Data on working hours for different economic sectors and for energy processes were obtained from the National Accounts Employment data [66] and from the Annual detailed enterprise statistics for industry [67], respectively.

3.1.2. Data on local and imported energy commodities

Data on local, imported and exported energy commodities were obtained from the Eurostat commodity balances [68]. Processors shown in Fig. 4 were included in the accounting of externalization. Firstly, traded energy commodities were identified using the Eurostat commodity balance [68]. Secondly, the identified commodities were associated with a set of intensive processors, i.e. processors where input and output flows are scaled per unit of energy commodity supplied, over their supply chain, according to the relations shown in Fig. 4. Thirdly, intensive processors were scaled up and aggregated into categories to accommodate statistical categories (e.g. lignite mining and coal mining were summed into ‘mining of coal and lignite’).

3.1.2.1. Energy Carriers & Labour in EUM_{EXT}. Intensive technical coefficients (energy carriers, in thermal equivalent) per unit of output, depending on the energy commodity, were taken from Ecoinvent [69] and scaled up using values of imported energy commodities as multipliers. The processes included in the accounting of the externalized matrices are detailed in Fig. 4 and then aggregated to accommodate statistical categories (see Supplementary Material for further details).

Data on working hours for different energy processes were obtained by scaling down statistical data [67] using local produced energy commodities and then re-scaling the data using imported energy commodities as multipliers.

3.1.3. Environmental pressure matrix (EUM) and data sources

3.1.3.1. GHG emissions & stock depletion in EPM_{INT}. Local stock depletion of hard coal, crude oil, lignite, natural gas and uranium were assumed from the statistical data on local supply [68].

GHG emissions, expressed in CO_2 equivalent (including CH_4, CO_2, HFC, N_2O, PFC, $NF_3\_SF_6$) for the processes of electricity supply, heat supply and manufacturing of coke and refined petroleum products were taken from the Eurostat Air Emissions account data [70], while GHG emissions in extraction of crude oil and natural gas, mining of coal and lignite and manufacturing of uranium were calculated by upscaling technical coefficients from Ecoinvent [69], as they are not available via Eurostat.

3.1.3.2. GHG emissions & stock depletion in EPM_{EXT}. Externalized stock depletions of hard coal, crude oil, lignite, natural gas and uranium were calculated by summing the directly imported primary energy sources, taken from Eurostat commodity balances [68], and the indirectly imported primary energy sources, calculated by upscaling technical coefficients to produce the imported energy carriers (e.g., the crude oil needed to produce imported fuels).

GHG emissions, expressed in CO_2 equivalent (including CH_4, CO_2, HFC, N_2O, PFC, $NF_3\_SF_6$) were calculated by upscaling the intensive technical coefficients (energy carriers, in thermal equivalent), depending on the energy commodity. The technical coefficients were taken from Ecoinvent [69] and upscaled using imported energy commodities as multipliers. The processes taken into account for the externalized matrices are detailed in Fig. 4 and then aggregated to accommodate statistical categories (see Supplementary Material for further details).

3.1.4. Assumptions

For all EU19 countries, the EUM_{EXT} and EPM_{EXT} were calculated by using average European processors. This means that results on externalization are approximate, as they assume that all the energy commodities are extracted/mined/processed using average European technical coefficients. Data for Luxemburg are not shown, as around 45% of the Luxembourg workforce is composed of cross-border workers [71], which affects the relations over constituent components inside the metabolic patterns.

3.2. Using the macroscope to characterize the size of the energy sector within the economy

An overview of the different energy uses in the European economy is illustrated in Fig. 5 (a and b). In Fig. 5a, labour (expressed in hours) and the energy carriers (expressed in MJ thermal equivalent) metabolized in the different sectors are shown for each country, on a per capita basis. As the share of hours spent in non-working activities (including physiological overhead, leisure, study, etc.), usually accounted in the household sector, is far larger than the hours in the paid work, the former (usually accounting for 80–90% of total yearly hours in post-industrial societies [72]) is not shown in the figures to make the hours allocated to the different economic sector more readable. In Fig. 5b, the information is given in terms of Energy Metabolic Rates (i.e. energy consumed per hour of labour) [21,73], for cross-country and cross-sector comparability. When assessed within the whole economy, the energy sector shows a limited contribution to the countries' total energy consumption (i.e. end-uses) and a marginal requirement of labour: it contributes to around 10% of the EU19's total energy consumption and to 3–4% of total working hours. However, despite the variability in different EU19 countries, Fig. 5b shows that this sector has the highest EMR, expressed as MJ/hour of work. This can be considered as a proxy of the level of technical capitalization of the sector. Confirming the results of previous studies [21,74,75], the high level of technical capitalization per worker explains the low fraction of the work force employed in this sector, compensated by a huge labour productivity in terms of net supply of energy carriers per hour of labour.

As can be seen in Fig. 5b, the EMR of the energy sector varies significantly from one country to another (it shows the largest range of variability among the economic sectors in the box plot) as it strongly depends on resource availability and the openness of the economy. Most European countries import crude oil to cover their consumption, some refine it, while other directly import refined products. This implies that if we want to understand the factors

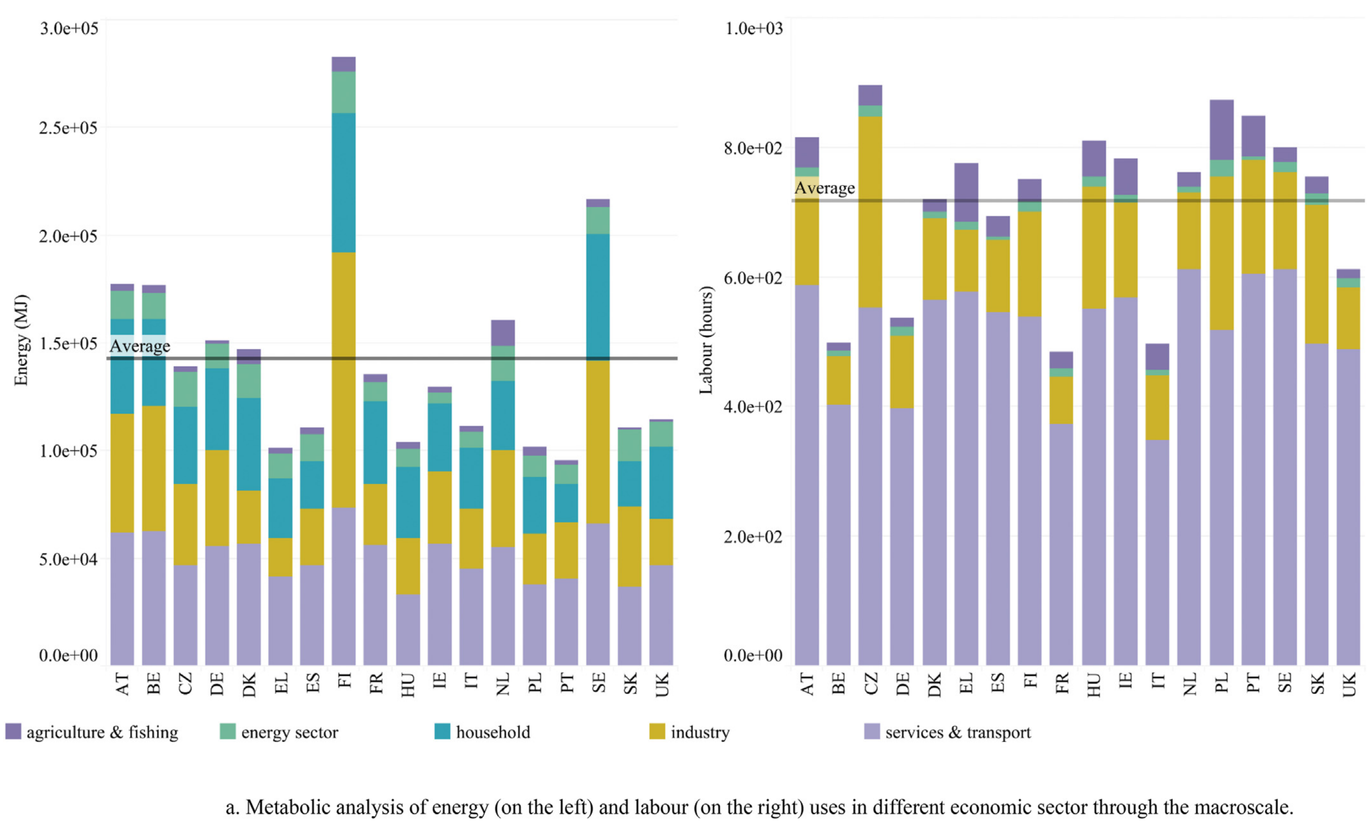
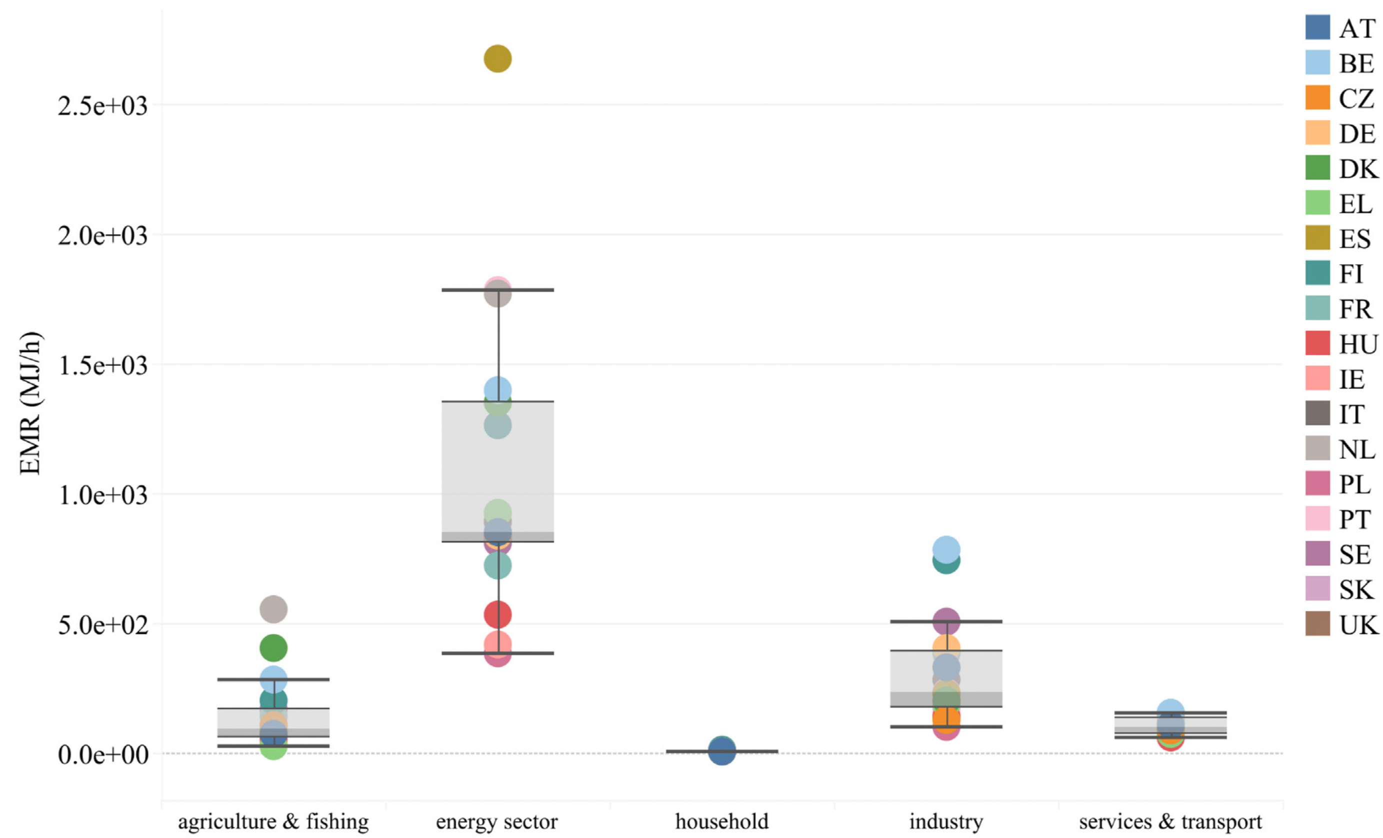


Fig. 5a. Metabolic analysis of energy (on the left) and labour (on the right) uses in different economic sector through the macroscale.



b. Metabolic analysis of energy and labour uses, through the EMR, in different economic sector through the macroscale.

Fig. 5b. Metabolic analysis of energy and labour uses, through the EMR, in different economic sector through the macroscale.

determining the performance of this sector, the processes taking place at a lower level of analysis and the level of imports and exports of the different energy commodities need to be considered.

3.3. Using the mesoscope to determine the openness of the energy sector

3.3.1. Internal and external End Use Matrix of the energy sector

Starting from the data on imported energy carriers (e.g. electricity and fuels), it is possible compare the quantities of energy carriers and labour used locally (internally) with how much has been invested abroad (externally) to produce the imported energy commodities. Information on the former is collected in the EUM_{INT}, on the latter in the EUM_{EXT}. These assessments are given in Fig. 6 and show that there is a low dependence on virtual labour (negative values) in the energy sectors of the sample of EU countries: on average, 13 h per capita per year are invested to produce all the energy carriers used (i.e. consumed and exported) by the EU, out of which 9 h are metabolized locally and around 4 h are indirectly imported (i.e. ‘virtual labour’) via direct imports of energy commodities. The Netherlands stands out by externalizing three times (around 15 h of labour per capita per year) the working hours invested locally (around 5 h of labour per capita per year) to produce the energy it requires. Regarding the externalization of energy carriers (expressed in MJ thermal equivalent), Fig. 6 shows that, on average, half of the energy needed to supply the energy carriers used by EU is externalized, meaning that it is indirectly imported via direct energy (commodities) imports. In general, the fact that the energy sector externalizes only a limited share of labour is coherent with the analysis at the macroscope level, where the energy sector is the most capitalized sector, with highest EMR.

A more detailed analysis of the EUM_{EXT}, considering a breakdown of the different processes using secondary energy and labour, is included in Supplementary Material. At this level of disaggregation, we can analyze the relative weight of the various processes included in the energy sector of a country. For example, most energy carriers are metabolized in the ‘electricity & heat supply process’ and ‘manufacture of coke & refined petroleum products’, while most of the working hours are invested in ‘electricity & heat supply process’ (see Figure SM1 in Supplementary Material). All in all, countries mostly importing primary energy sources are more likely to externalize labour, as mining and extraction are more labour demanding. A special case is the Netherlands which is completely externalizing the labour and energy carriers needed to supply crude oil and fuels, either used for local consumption or for exports.

3.3.2. Internal and external environmental pressure matrix

As in Section 3.3.1, starting from the data on imported primary energy inputs (e.g. crude oil, natural gas, coal), we calculate and compare the quantities of primary energy sources that are taken from the biosphere (considered as stock depletion), the GHG emissions happening locally (mapping onto the EUM_{INT}), the quantities of primary energy sources externalized abroad (both directly and indirectly) and the externalized GHG emissions (mapping onto the EUM_{EXT}). These assessments allow a comparison between the internal and the external environmental pressure matrix. Comparisons are given in Fig. 7 (a, b) in relation to two

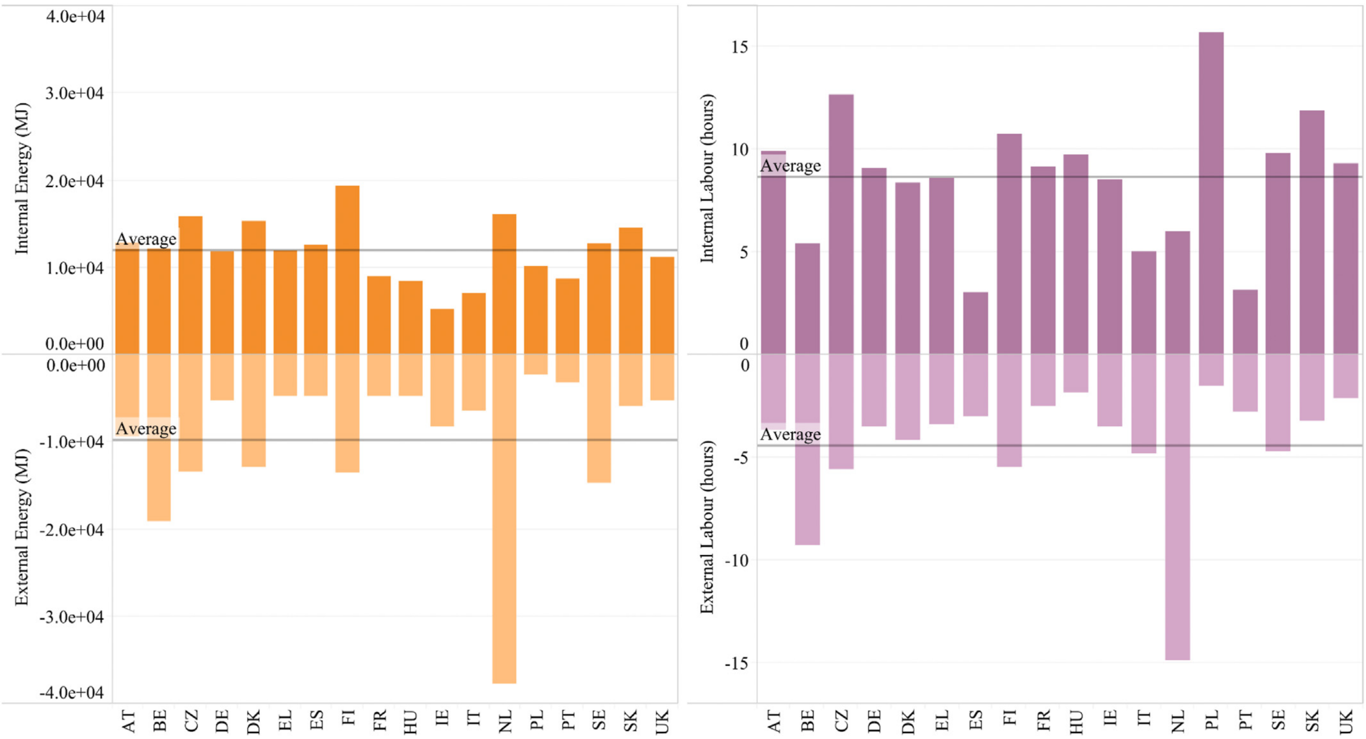
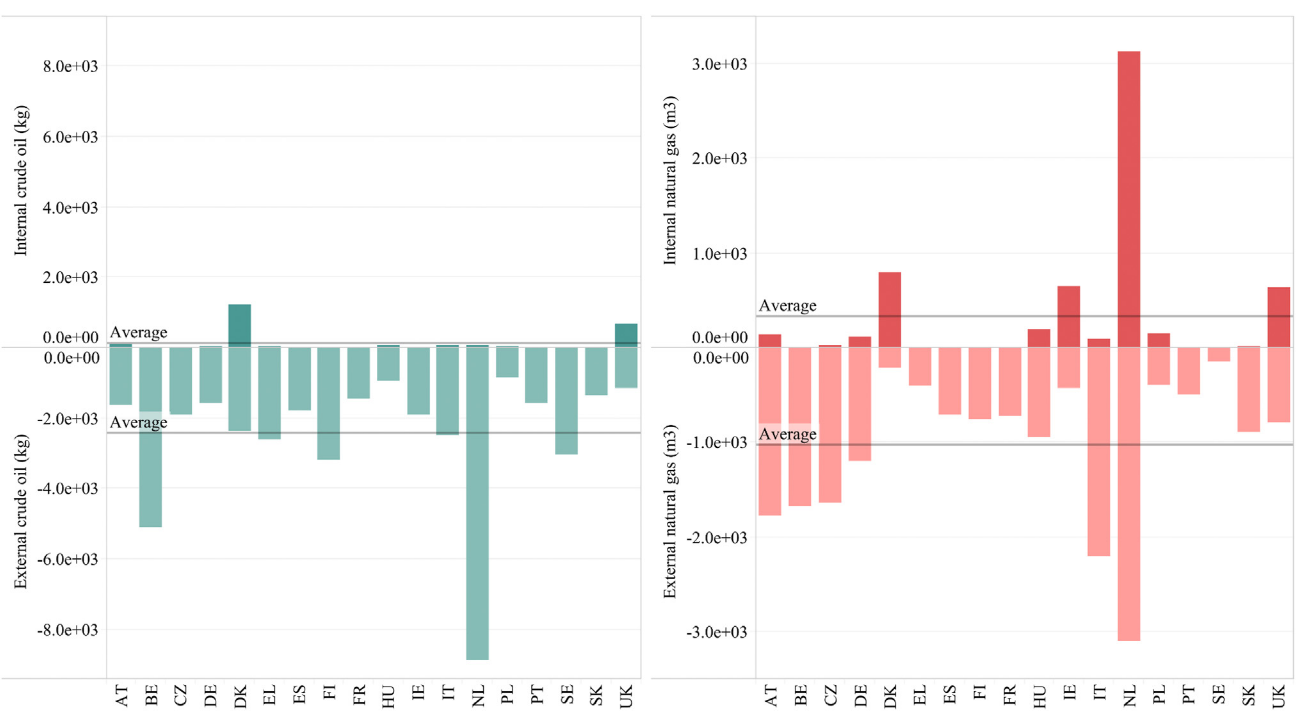
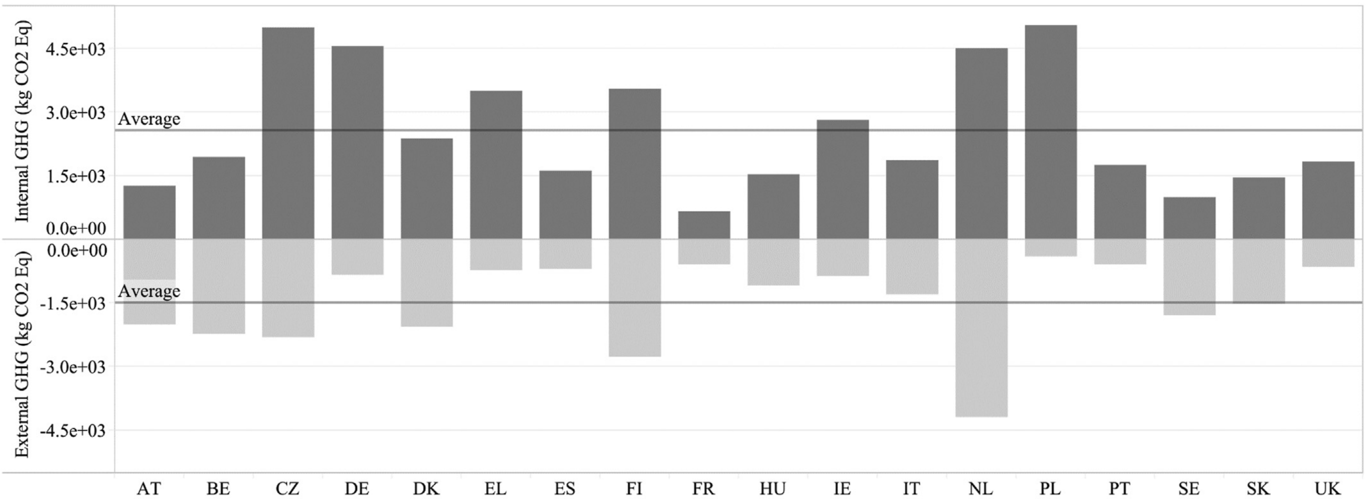


Fig. 6. End Use Matrix (internal and external) showing the consumption of energy carriers per capita per year (on the left) and labour per capita per year (on the right) for the energy sector - EU19 (year 2016). Positive values (and dark colours) depict internal consumption while negative values (and light colours) depict external consumption. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



a. Environmental Pressure Matrix (local and external) over stock depletion of PES (kg/m3 per capita) for crude oil (left side) and natural gas (right side) - EU19 (year 2016). Positive values (and dark colours) depict internal environmental pressure while negative values (and light colours) depict external environmental pressure.

Fig. 7a. Environmental Pressure Matrix (local and external) over stock depletion of PES (kg/m3 per capita) for crude oil (left side) and natural gas (right side) - EU19 (year 2016). Positive values (and dark colours) depict internal environmental pressure while negative values (and light colours) depict external environmental pressure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



b. Environmental Pressure Matrix (internal and external) over emissions of GHG per capita - EU19 (year 2016). Positive values (and dark colours) depict internal environmental pressure while negative values (and light colours) depict external environmental pressure.

Fig. 7b. Environmental Pressure Matrix (internal and external) over emissions of GHG per capita - EU19 (year 2016). Positive values (and dark colours) depict internal environmental pressure while negative values (and light colours) depict external environmental pressure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

different forms of environmental pressure: (i) the stock depletion of non-renewable PES: hard coal and brown coal, crude oil and natural gas; (ii) GHG emissions. For sake of readability and space, figures related to crude oil, natural gas and GHG are reported while the rest of the figures is included in Supplementary Material (see Figure SM2).

When looking at the externalized environmental pressures, Fig. 7a shows how the EU is dependent on external primary energy sources, especially crude oil. If directly imported oil (usually reported in the official statistics) and indirectly imported oil (i.e. embedded in the direct imports of energy commodities) are accounted for and compared with the local supply of oil, it is easy to conclude that the dependency rate, on EU average, is almost 100%. Similarly, accounting for the externalized carbon emissions of the energy sector raises total GHG emissions of the sector by 60% on EU average.

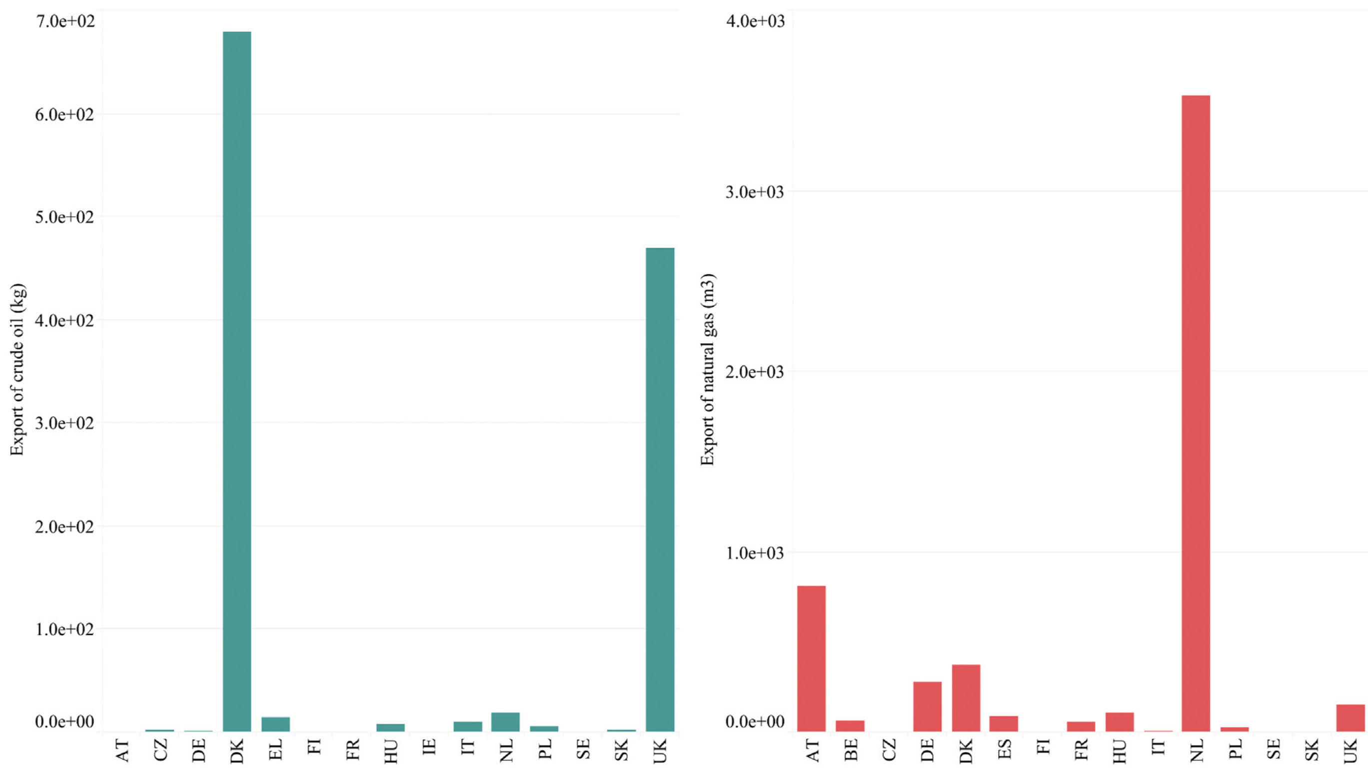
In order to flag the distortion caused by the trade of energy commodities on the assessments carried out at the national level, Fig. 8a shows an example of PES exports (countries not shown in the figures are the ones that do not export PES) and Fig. 8b shows the exports of EC. Two points are clear from Figure 8a: (i) the export of PES is not a common activity in EU; and (ii) the export of PES reflects the existence of particular situations in specific countries. With respect to oil dependency, two countries, Denmark and UK, stand out as they are among the largest exporters of oil in EU. The Netherlands is a big importer and exporter of PES (especially natural gas), due to the intense activity of Dutch ports, while Czech Republic, Poland and Hungary export coal because of the availability of local reserves (see Figure SM3 in Supplementary Material). In relation to the exports of EC - shown in Figure 8b — the Netherlands is by far the largest exporter of fuels in the EU, with fuels accounting for close to one quarter of all Dutch exports and making up a good part of Dutch economy (the 17th largest economy in the world [76]). This piece of information complements the analysis provided in the macroscope, as Netherlands is also one of the countries with the highest share of working hours in services and in transport. This is directly related with the material standard of living [18,72].

3.4. *Using the microscope to assess the impact at the local level*

When moving to the analysis of the flows of energy at the local level, we can study the impact that these flows have on the environment. To study the impact of the energy metabolism, the primary flows required on the supply side can be compared with the available supply capacity, whereas to study the impact on the sink side the primary flows of emissions can be compared with the absorbing capacity of the ecological funds affected by emissions. Here, we focus on the stock depletion of non-renewable primary energy sources. As illustrated in Figure 7, we can use the assessment of the quantity of PES consumed as an indicator of an environmental pressure - the amount of stock depletion associated with the stabilization of that specific primary flow. In the case of renewable resources, for example biomass, the impact of the primary flows can be estimated by looking at the consequences of the production of the primary flow of biomass on ecological funds. This includes excessive abstraction of water from aquifers and excessive leakage of phosphorous and nitrogen in the water table in the phase of biomass production. In the case of non-renewable primary energy sources, the years of exploitation left of the available reserve can be used as an indicator. An example of this analysis is given in Fig. 9, to give an idea of the precarious situation of the stocks of primary energy in Europe. Here the years left are calculated considering the ratio between the reserves left in the country (data taken from US-EIA [77]) and the total calculated primary energy sources used by the country (i.e. the sum of locally extracted and - directly and indirectly - imported primary energy sources).

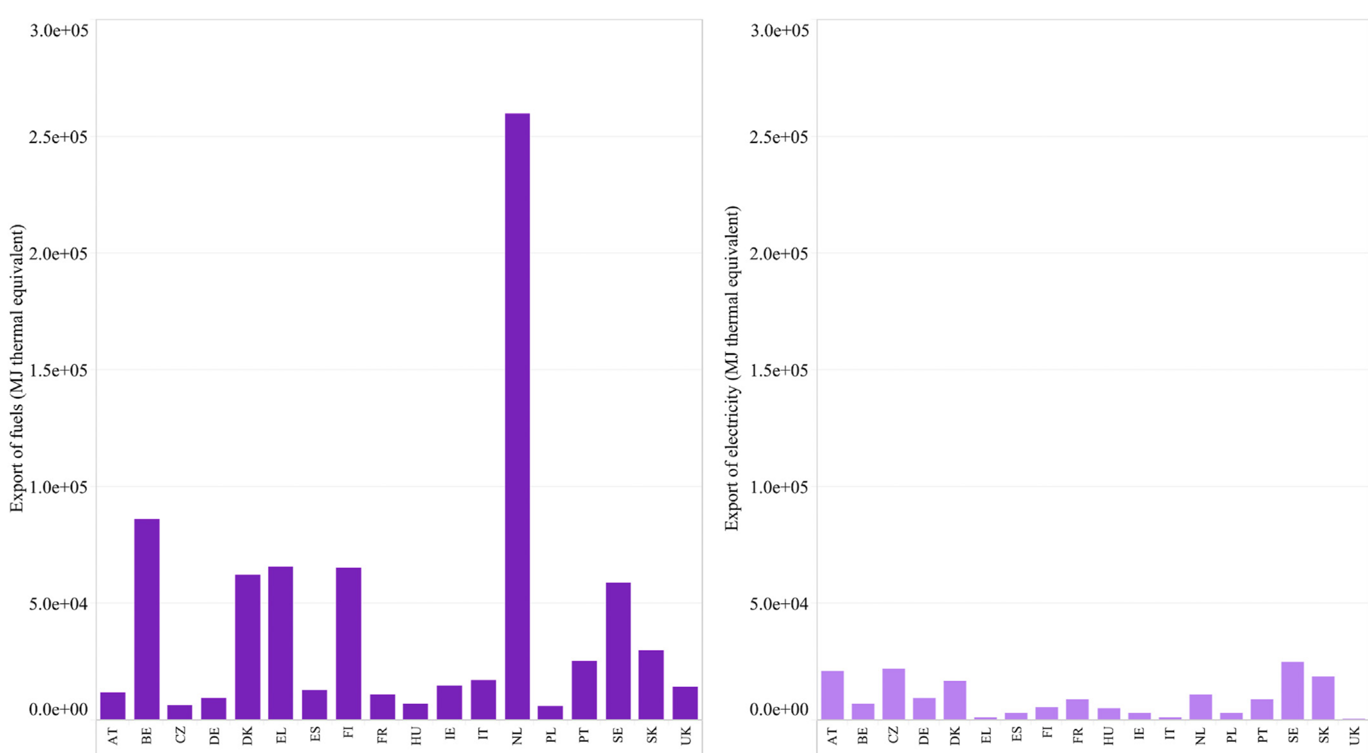
4. Conclusions

Post-industrial societies in the globalized world rely on trade for the survival of their identity. This means that given the availability of resources, their systems of production are (and must be) open in order to match consumption patterns. In addition to being open, production systems are complex, posing challenges for both governance and modelling. Energy systems are formed of sequential pathways of transformations that are located within and outside governance boundaries. The different steps of these



a. Exports of PES (crude oil and natural gas) - EU19 (year 2016). Countries not shown in the figure are those not exporting PES.

Fig. 8a. Exports of PES (crude oil and natural gas) - EU19 (year 2016). Countries not shown in the figure are those not exporting PES.



b. Exports of Energy Carriers (fuels and electricity) - EU19 (year 2016).

Fig. 8b. Exports of Energy Carriers (fuels and electricity) - EU19 (year 2016).

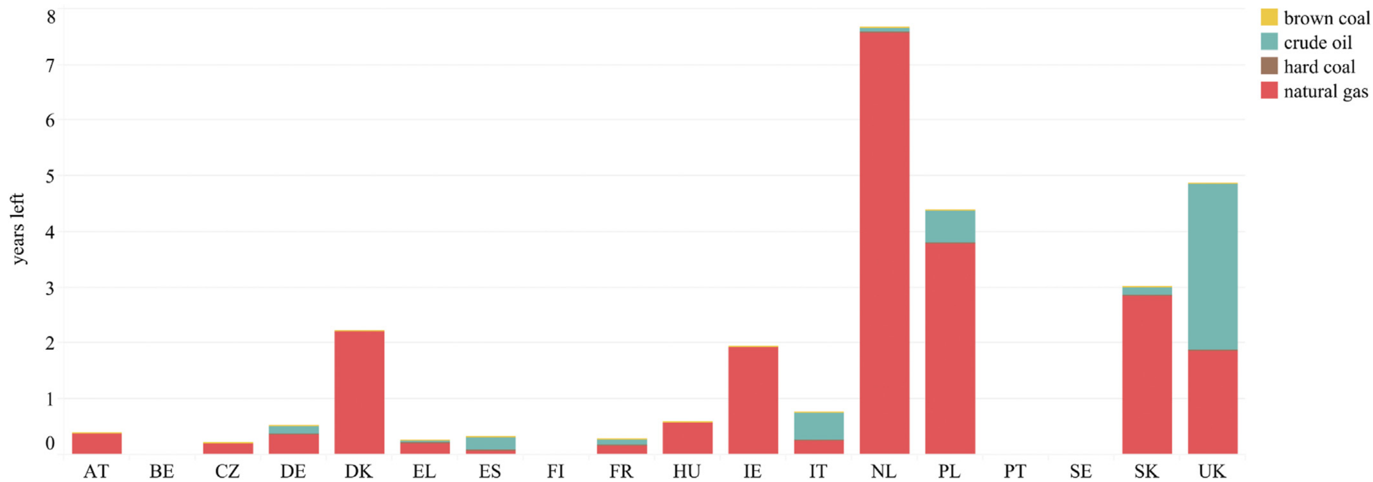


Fig. 9. Years left to local stock depletion (local reserves/total primary energy source used in a year) - EU19 (year 2016).

sequential pathways require investments of labour, emit GHGs, and deplete stocks. This paper focused on the challenges that the openness of systems poses for modelling the energy sector.

We introduced a methodology, grounded in the conceptualization of societal metabolism, aimed at accounting for the externalization of production processes at different scales. The methodology relies on a disaggregation of energy products, which is necessary for understanding how individual energy supply systems fit within the metabolism of the system as a whole, and for understanding how to detect and assess environmental impacts at the local level. We proposed three levels of analysis to be used in describing the behaviour of a system's energy sector: the macroscale, the mesoscale and the microscale.

Through the macroscope, the energy sector can be analyzed as a whole made of interacting parts, and the interactions of economic sectors can be explored. The analysis for EU19 countries showed how the energy sector contributes to approximately 10% of their energy consumption. The exosomatic metabolic rate of the sector, i.e. the amount of energy consumed per hour of labour, is the highest across the economies of each country, due to the energy sector's high labour productivity. Moving to the mesoscope, we can explore the implications of the openness of the system. Results for EU19 countries showed how direct and indirect imports of primary energy sources and energy carriers can paint a different picture of the performance of the energy sector than what is seen when only focusing within the countries' boundaries. Looking at GHG emissions, for example, results show that, on EU average, the total GHG emissions of the sector rise by 60% when externalized processes are accounted for. A microscope analysis, finally, allows mapping processes of the energy sector onto specific environmental impacts. Comparing the consumption of primary energy sources to available stocks, the results show that if EU19 countries were to rely solely on locally available stocks, they would rapidly run out of stocks.

As for any methodology, there are limitations on the usefulness of the quantitative assessment generated here. The accuracy of the assessment of the differences across countries may be affected by the choices made: (i) when bridging the non-equivalent metrics — i.e. how the total amount of metabolized energy carriers is mapped on the total amount of required supply systems (to generate the locally produced and imported energy commodities); (ii) when determining the processors describing the profiles of inputs and outputs used in the various processes of "energy transformations" assumed to take place in the supply systems. The proposed analysis is based on a triangulation between the calculated data about externalization (which are determined by intensive variables) and local statistical data (which are given as extensive and sometimes as product-aggregated categories). Depending on the circumstances, mismatches between the two types of data require assumptions from the analyst.

The methodology proposed in this paper adds to the body of existing literature calling for more robust and transparent approaches to be used when informing energy policies. The multiscale accounting of externalization based on societal metabolism can contribute to a richer understanding of the existence of limits and of the broader environmental consequences of economic development and social functioning in a globalized world.

Credit author statement

M. Ripa: Conceptualization, Methodology, Data curation, Investigation, Writing- Original draft preparation, L. J. Di Felice: Writing- Reviewing and Editing, M. Giampietro: Writing- Reviewing and Editing, 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.energy.2020.118943.

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