Analyzing the energy performance of manufacturing across levels using the end-use matrix

Raúl Velasco-Fernández [a, *], Mario Giampietro [a, b], Sandra G.F. Bukkens [a]

[a] *Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*
[b] *ICREA, Passeig Lluís Companys 23, 08010 Barcelona, Spain*

ABSTRACT

Within the context of the controversial use of the concept energy intensity to assess national energy performance, this paper proposes an innovative accounting framework: the energy end-use matrix. This tool integrates quantitative assessments of energy use of the various constituent compartments of socio-economic systems. More specifically it identifies, moving across levels of analysis, what compartments (or sub-compartments) are using what type of energy carriers for what type of end-use. This analysis is integrated with an assessment of labor requirements and the associated flows of value added. The end-use matrix thus integrates in a coherent way quantitative assessments across different dimensions and hierarchical scales and facilitates the development of integrated sets of indicators. In this way it contributes to a multi-criteria characterization of national or sectoral energy performance. The tool is illustrated with an analysis of three EU countries: Bulgaria, Finland and Spain. Challenges to improving the usefulness of biophysical analysis of the efficiency of the industrial sector are identified and discussed. Increasing the discriminatory power of quantitative analysis through better data standardization by statistical offices is the major challenge.

© 2018 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Energy efficiency and decarbonization are an integral part of the EU 2020 Energy Strategy [1]. They were also core to US energy policies [2] before the Trump administration drastically changed policies related to climate change and oil, gas, and coal exploration [3]. Energy intensity and carbon intensity in particular have become popular indicators for assessing the sustainability of modern economies. However, despite their ubiquitous use, practical [4] and conceptual problems [5] encountered in the implementation of the concept of energy efficiency have received little attention in academics [6]. This is remarkable not only from a technical view, but also from a social science [7] and political perspective [8], given the value judgements incorporated in the concept [9] and the potential political implications [10].

The formulation and use of measures of energy efficiency is tightly linked to the development of thermodynamics. However, one of the very fathers of thermodynamics, Sadi Carnot, warned in

1824 that *"the economy of the combustible"* is just one of the relevant issues to consider and *"in many cases it is secondary"* [11]. Carnot suggested that a more sophisticated integrated analysis of the performance of thermal engines should be based on multiple indicators [11]. The same message was conveyed by Phylipsen et al., in 1997: *"The energy efficiency of economic processes cannot easily be measured since it is determined by a myriad of processes taking place serially or in parallel"* [5]. The epistemological problems faced in quantifying energy transformations across different levels were discussed extensively in the 1970s when the discipline of energy analysis was born. As indicated by Maddox [12] *"Net energy analysis was the initial response to an analytical problem of how to measure the efficiency of energy systems"* (p. 142). Several epistemological conundrums were identified, such as the truncation problem (arbitrary definition of boundaries) [13], the joint production dilemma [14], and the differences in quality of different energy forms (mechanical and thermal) [15]. It should be noted that the scope of these energy analyses was broad, including the implications of the pre-analytical choice of boundary or how to handle the coexistence of different energy forms with different qualities and different time scales on the energy return on investment, discount rate, labor requirement, roles of institutions, and impact on

---

ecosystems [16,17]. For an overview of the discussion, see Giampietro et al. [18].

Current use of the economic energy intensity indicator tends to ignore the complexity of the issue at hand and its related epistemological problems. This is a reason for concern. Energy intensity is commonly defined as an output/input ratio obtained by aggregating characteristics that are different when observed from different hierarchical levels (e.g., individual plant, sub-sector, economic sector, whole economy) [18], and ignoring differences in the energy mix [19] as well as energy-labor substitution [20] or structural changes [21].

At the local (process) level, managers and efficiency analysts are generally well aware that efficiency issues requires them to go beyond unique input-output ratios at the level of the process [22], considering different levels [23] and different issues, such as CO_2 emissions [24], energy consumption [25], behavior of production workers [26], integration of the different processes over the entire production operation [27], and the integration of multiple scales in the analysis [28]. But when it comes to energy and carbon intensity at societal level, it is still common practice to measure 'the' energy performance of national economies even though it does not provide discriminatory power in cross-country comparisons [29], overlooks potential unexpected consequences when trying to reduce energy consumption with more efficient processes [30], and totally ignores the implications of multilevel analysis [18]. Especially in cross-country comparisons and longitudinal studies at the national level, the indicator produces numbers that are void of meaning [29]. Indeed, it has been suggested that quantitative analysis should be organized hierarchically taking into account factors and sub-factors (at different levels) and their relative importance in determining the aggregate result [31]. This implies considering structural differences in time or among national economies [32]. Others have pointed out the analytical importance (at the level of the national economy) of shifting energy intensive activities abroad by deindustrializing the economy and relying on imports [33].

In an attempt to overcome these shortcomings, we propose and illustrate a more holistic approach to the analysis of societal energy use based on multi-scale integrated analysis of the energy metabolism of social-ecological systems. This approach consists in a coherent organization of the data describing energy end-uses in the form of a multi-level data array or 'end-use matrix'. The end-use matrix integrates information on where and how energy carriers are used in the socio-economic system across different hierarchical scales of organization. In this paper we will focus in particular on the application of this tool to the analysis of the metabolic pattern of the industrial sector (building and manufacturing) given its dominant role in determining the energy and carbon intensity of the economic process (the industrial sector accounted for 36% of total electricity consumption in European Union in 2012 [34]).

In the following section (section 2), we first discuss the caveats of the use of energy intensity as an indicator of energy performance (note that we use the term energy performance in the sense suggested by Georgescu-Roegen as a reading of the economic process based on the tracking of its biophysical processes [35]). In section 3, we propose a new take on the study of societal energy use based on Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM); and then, in section 4, we illustrate this approach by examining and comparing the industrial sector of three European countries, Bulgaria, Finland, and Spain at various hierarchical scales of analysis. Finally, in section 5, we conclude with a discussion of the pros and cons of the proposed approach to evaluate the energy performance of the economy.

2. Caveats of the use of energy intensity as an indicator for energy performance

In this section we show that neither at the aggregate level of the whole economy nor at the level of individual economic sectors, energy intensity and energy efficiency are effective concepts for an analysis of energy performance of a complex system. While a simple ratio, such as energy/GDP, is obviously attractive and easily calculated from available statistics, it has little information content if not properly contextualized within the larger metabolic process to which it refers [18].

In order to illustrate the limitations to the use of energy intensity as an indicator for energy performance, we represent modern society as a social-ecological system, as shown in Fig. 1. In our representation, we single out the energy sector (on the left) and group the other sectors (on the right) including the industrial sector, service and government sector, transportation sector, and residential sector. The energy sector is where primary energy sources are exploited to produce energy carriers, the rest of the economic process uses energy carriers to express its functions.

In Fig. 1 we indicate five factors that influence the energy intensity and carbon intensity associated with the metabolism of a social-ecological system, and notably its energy use in relation to the GDP. These five factors need to be carefully addressed for energy intensity or energy efficiency to have any meaning at all:

1. The degree of openness of the energy sector;
2. The mix of primary energy sources and energy carriers used in society;
3. The mix of economic activities carried out in society;
4. A selective externalization of economic activities (import of goods and services);
5. Credit leverage and quantitative easing boosting the GDP.

2.1. The openness of the energy sector

Fossil energy imports represent an externalization of the cost of producing energy carriers in terms of required investments in technology, labor, water, land use, and obviously of the required availability of primary energy sources. Fossil energy imports also
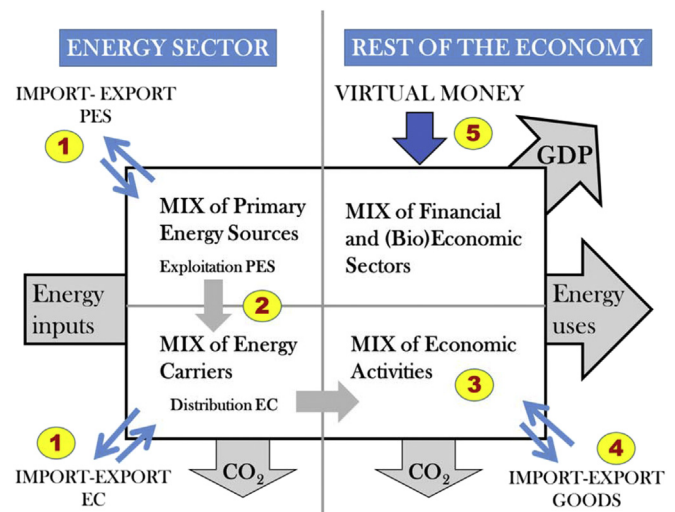

Fig. 1. The different factors affecting the energy and carbon intensity of an economy. Abbreviations: PES = primary energy sources; EC = energy carriers; GDP = gross domestic product.

externalize the emissions of CO_2 (and other socio-environmental impacts [36]) in the phases of extraction, refinery and transport. Indeed, energy import is key to maintaining a reduced consumption of primary energy sources and energy carriers in the operation of developed economies, notably in Europe. The importance of this factor becomes evident if we look at the energy consumption in oil exporting countries: about 3–10% of the energy of exported oil is consumed locally for oil extraction, 10–15% for refining, and another 2% for transportation [37,38]. Thus, an additional 15–20% of energy consumption is embodied in the imported fossil energy consumed by developed countries. This bonus is generally not considered in the calculation of the energy intensity of the economy (a recent attempt to deal with this issue can be found in Ref. [39]).

2.2. The mix of primary energy sources and energy carriers

In Fig. 2, we show the three sets of categories that are relevant for the accounting of energy: primary energy sources, energy carriers, and end-uses [40]. For each category we list various examples.

Primary energy sources (PES) are energy forms that cannot be produced by humans. Their (lack of) availability therefore represents an external constraint that limits the use of energy. Primary energy sources can be of various forms: mechanical (wind, hydro, waves), thermal (concentrated solar power, geothermal), chemical stocks (fossil energy such as coal, oil), or nuclear (generating thermal energy). Primary energy sources can be divided into renewable and non-renewable sources as shown in Fig. 2.

When a big difference exists among countries in the mix of primary energy sources used to generate electricity, we cannot compare the energy performance of a sector or the whole national economy by simply measuring the energy or carbon intensity. For example, a country producing more than 90% of its electricity with hydropower, such as Norway, requires less fossil energy and emits less CO_2 to supply the same amount of electricity than a country

such as Poland relying predominantly on coal power plants (about 85%) [41]. In this case, the difference in the value of energy intensity is not generated by a difference in the efficiency of the technologies used in the power plants, but by the mix of PES used to produce electricity.

Energy carriers (EC) (or secondary energy) are energy forms under human control that are produced from available primary energy sources. As shown in Fig. 2, different types of energy carriers are used for different purposes (end uses) by different end users. Airplanes do not fly on electricity and laptops do not run on kerosene. If we want to assess the efficiency of a refrigerator we need data on the electricity it consumes; if we want to assess CO_2 emissions we need data on the carbon-based fuels that have been burned. Also in this case, different mixes of economic activities will require different mixes of energy carriers, which in turn may be produced from different mixes of PES. Hence it simply does not make sense to use a single quantitative assessment of 'energy use' in the analysis of energy (or carbon) intensity. Aggregate energy consumption assessed as tons of oil equivalent does not allow the identification of a unique relation between the performance of the economy (measured by the GDP) and the 'overall energy consumption' (which can be expressed either in quantities of PES or quantities of EC). Let alone the establishment of a unique relation between economic performance and tons of CO_2 emissions.

The aggregation of different energy forms into a single quantitative assessment of 'energy use' implies loss of information by default [40]. For example, if we have a mix of 30 GJ of electricity and 70 GJ of fuel, we could aggregate them into a single assessment of 'energy use' using the partial substitution method: the joules of electricity are multiplied by a conversion factor of 2,65 before being summed to the thermal joules. In this case, we would arrive at a total of 150 GJ of gross energy requirement (PES, thermal energy equivalent) or about 3,6 TOE. Other methods of aggregation exist (e.g., the one adopted by Eurostat and IEA) that will (or not) result in a different gross energy requirement depending on the mix of
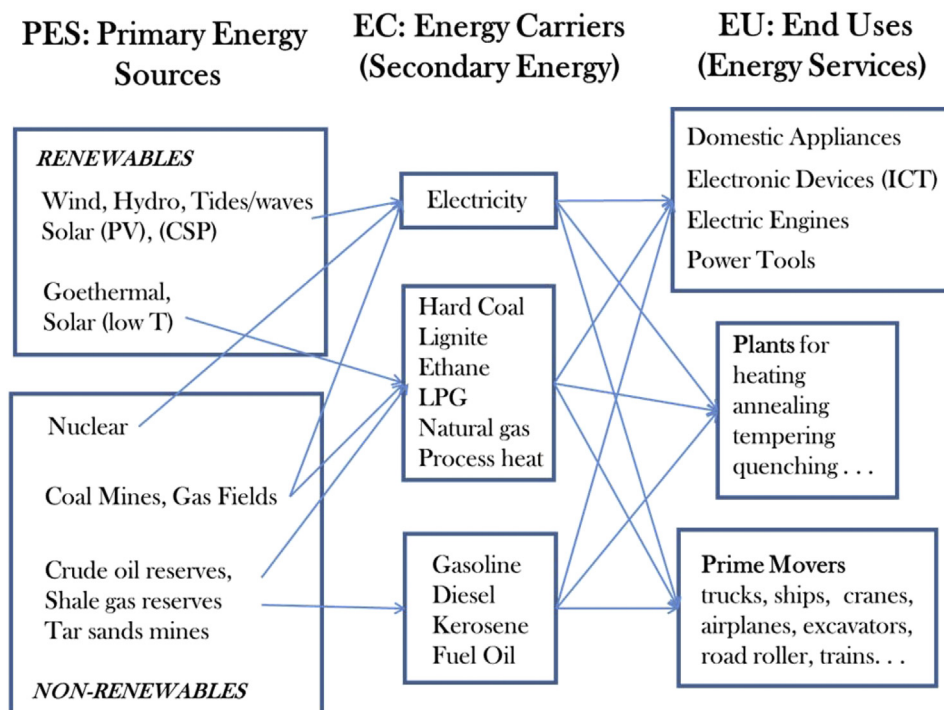

Fig. 2. Examples of the different categories in energy accounting.

primary energy sources used to generate electricity [18].

2.3. The mix of economic activities carried out in society (structural factors)

The energy intensity of the economy as a whole is determined by the energy intensities of its end-use sectors (that is, by the mix of goods and services produced and consumed). Indeed, the relative weight of the more and less energy intensive end-uses (sectors, subsectors, processes) in the economy is a key factor in determining the energy intensity of the economy as a whole. For example, an economy deriving most of its GDP from metal, chemical and/or paper industries will have a higher energy intensity than an economy deriving most of its GDP from the financial sector. In this case, again the mix of economic activities will result far more important in determining the overall economic energy intensity (or the carbon intensity) than the efficiency of the technologies used in each one of the individual end-uses. For example, a post-industrial society based on an outdated tourism sector will result less energy intensive than an industrial society based on state-of-the-art metallurgic production [18]. Indeed, a major structural factor behind reductions in aggregate energy intensity in manufacturing in many countries has been the relative decline of the role of energy-intensive industries (e.g., primary metals, chemicals, and paper) in the generation of the GDP [18].

2.4. Externalization of industrial production through imports

Related to the previous point, the energy intensity of an economy can be significantly reduced by externalizing the most energy intensive end-uses to other countries.

Indeed, through import of raw materials, semi-finished products or end-products, a society can externalize the consumption of energy (and relative carbon emissions) required to produce these goods. In this case we can say that the relative energy (and material) consumption and emissions (as well as other socio-environmental impacts [36]) are *externalized* to the country producing the imported goods. As a matter of fact, by externalizing the burden of industrial production (the most energy-intensive economic sector) to countries like China, Russia, Brazil or India [42], many developed countries have significantly reduced their energy and carbon intensity (decarbonization). This achievement has been associated with a process of deindustrialization of their economy [43], but this should not be associated with an 'improvement' in the technical efficiency of their economies.

2.5. Credit leverage and quantitative easing as non-biophysical factors boosting economic efficiency

Reliance on credit leverage and quantitative easing (debt) can boost the national GDP without a concomitant increase in energy use and relative CO_2 emissions. Indeed, a continuous massive injection of liquidity based on an increase in debt into the economy allows for the importation of goods 'free' of the concomitant biophysical costs — the biophysical cost of production is externalized. If imported goods were to be paid with an equivalent amount of value added obtained by producing and exporting goods — with monetary flows mapping onto actual quantities of value added produced with biophysical transformation in the economy - they would imply energy use and CO_2 emissions, for generating that value added. A recent report of the McKinsey Global Institute [44] indicates that since 2007 the global debt (in the form of credit leverage or quantitative easing) has increased by 57 trillion USD, outpacing world GDP growth. The same study indicates that developed countries have the larger amount of and larger rate of

increase in credit leverage and quantitative easing. If we would rely on the economic energy intensity of the national economy (total energy consumption/GDP) as an indicator of performance, we would find that importing goods and paying them with money obtained by making debts is by far the most effective strategy to boost the efficiency of the economy. According to this indicator we simply have to print more money in order to reduce CO_2 emission at the national level.

2.6. How to handle the analysis of all these factors?

We can wrap-up this section by using the overview of the different factors given in Fig. 1. A socio-economic system is a complex open system operating across different levels of organization that has to be described at different scales and using different dimensions of analysis (e.g. biophysical, socio-economic, environmental, demographic, financial, etc.). When dealing with this class of systems any quantitative indicator based on a simplistic compression of the variety of this rich set of attributes implies the unrecoverable loss of relevant information. Incoherent indices of energy efficiency are not good for this task. An informed discussion about the technological performance and energy use of modern economies needs a more elaborate analytical tool capable of identifying the different factors determining overall relations over flows.

3. Methodology

3.1. Theoretical framework: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

When analyzing the relation between 'the quantity of energy used' and 'the amount of GPD generated' for a metabolic system, we should not consider flows in isolation. Metabolic flows are meaningful only if they are contextualized in relation to the larger metabolic process in which they are used as useful input and produced as useful output. Using the flow-fund model proposed by Georgescu-Roegen [45] we can make an epistemological distinction between *flows* —quantities disappearing or appearing over a given period of analysis— and *funds* —structural elements of the metabolic system associated with agency (e.g., population, workers, technical capital or power capacity in energetic jargon) preserving their identity over the given period of analysis (see, for example, applications to societal metabolism [18], historical analysis [46] or political ecology [47]). Within this model, the sizes of the various flows are determined by the characteristics of the various processes taking place inside society [18]. In turn the size of these processes is determined by a combination of two types of information: (i) quantitative information—the size of the fund element measured using extensive variables (e.g., food eaten per year by a person); and (ii) qualitative information—the technical characteristics of the fund elements controlling the flows (consuming the inputs and generating the outputs) measured by intensive variables: unit of input (or output) per unit of fund (e.g., food consumed per year per person). The two pieces of information refer to different scales of analysis; the extensive variable refers to an overall consumption per year, the intensive variable to a pace of consumption per day (local scale) whose value is averaged over the year. Therefore, when using the flow-fund model we do not study 'the flow' of food consumption of a given society (e.g., a given amount of kcal/year), but rather the product of two terms: (i) the number of people in society in a year (the size of the fund element) multiplied with (ii) the consumption of food per person per year (a flow/fund ratio used as benchmark and defined at the local scale — e.g. per day — and then averaged per year) [48]. In this way, we can establish a

link between different sources of information (external referents) that are observed at different scales [12].

We propose a system of accounting based on the MuSIASEM rationale to examine the energy use and economic productivity of the industrial sector. MuSIASEM builds on the flow-fund model of Georgescu-Roegen as well as on complexity theory. The foundation of the theoretical framework [49] as well as the set of forced relations affecting the metabolic characteristics of the socio-economic process [50] have been described in detail elsewhere. Pastore et al. [51] provided an empirical validation. The approach has been fully formalized in Ref. [18], tailored to energy analysis in Ref. [40] and then expanded to the analysis of other metabolized flows [48]. Key features relevant to the work presented here include:

- Rather than reducing all energy forms into a semantically-void generic category of accounting, such as joules of energy commodities (used by Eurostat and IEA), we respect the specificity of the main energy carriers, electricity, process heat and fuel (that are specific inputs for specific end uses) and maintain their separate accounting throughout the analysis [52].
- We map the consumption of these energy carriers for all sectors and subsectors of the system and also consider an additional production factor: human labor (fund element) as a necessary ingredient to obtain stabilization of energy flows [18].
- For all sectors and subsectors of the system we map the allocation of fund and flow elements (biophysical inputs) onto the flows of value added generated [18].
- We define the size and hierarchical structure of the system on the basis of the allocation of the fund element human activity —defined as quantities of hours/year of paid work— to the various sectors and sub-sectors of the system. This taxonomy makes it possible to allocate to each (sub)sector of the system the relative flow elements (i.e., the different types of energy carriers and value added) associated to human activity [18].
- In this study, the social system as a whole is defined as having a total size (measured in hours of human activity) calculated as: number of people × 8.760 (hours in a year). The size of the different economic sectors and economic sub-sectors within the social system is defined as: "number of workers in the given sector" × "workload in the given sector expressed in hours per year".
- We use both: (i) extensive variables for assessing the size of fund elements: hours of human activity in a year, and flow elements: throughput of energy carriers and quantities of value added generated in a year; and (ii) intensive variables: flow/fund ratios, such as the throughput of energy carrier per hour of human activity (average value per year) allocated to the end-uses, and the quantity of value added generated per hour of human activity (average value per year) allocated to the end-uses.

Thus, we do not use the generic flow/flow ratio 'energy use' (flow element)/'GDP' (flow element)'. Rather we propose the combined use of two sets of flow/fund ratios: 'quantity of energy carrier per hour of labor' (specified by energy carrier type) and 'quantity of value added per hour of labor' (specified by job types) in a given compartment, that are multiplied by an assessment of the fund element 'human activity' (express in hours per year) invested in the same element. The latter assessment provides the scaling factor: the size of the fund human activity (labor hours) allocated to a given (sub)sector is used to scale its specific metabolic characteristics (defined by the flow/fund ratios). Hence the size of the flows associated with a (sub)sector are the product of an extensive variable (size of the fund — hours of labor) and an intensive variable

(the flow/fund ratio — quantity of the flow per hour of labor). This product must result consistent with the quantitative assessment of the flow obtained using statistical data. Indeed, in MuSIASEM intensive variables provide useful benchmarks describing the qualitative metabolic characteristics of the system's elements (i.e., the inputs required per unit of output). Extensive variables, on the other hand, reflect the size of the fund elements (human activity, the agent using and producing flows) scaling the information provided by intensive variables. The integrated use of intensive and extensive variable allows us to scale the metabolic characteristics of industrial sectors and subsectors within a country, and compare the performance of specific (sub)sectors across different countries. Moreover, the simultaneous accounting of these factors allows us to evaluate the behavior of the system and subsystems in relation to the implications of the coexistence of two contrasting principles: (i) the maximum power principle — stated in general terms by Lotka in relation to all living systems [53] and conceptualized in quantitative terms by Odum and Pinkerton [54]; and (ii) the minimum entropy generation principle — envisioned by Prigogine [55] and formalized within the field of non-equilibrium thermodynamics by his school [56]. The analysis of the coexistence of these two contrasting principle can be used to explain the occurrence of the Jevons' Paradox [30] in the system studied.

Inclusion of the intensive variable economic job productivity of a given sector (EJP_i) — the amount of value added generated per hour of labor in a specific (sub)sector i —is an important feature of MuSIASEM. It provides an indication —independent of energy use— of the convenience of externalizing economic activities (end-uses) to other countries. When the income provided by an economic activity is not or no longer competitive with other activities in the economic process (relative low EJP_i), then the activity is prone to shrink in size and eventually become externalized to low-income countries. This happened, for example, with the metallurgic sector in many European countries [57]. The analysis of these dynamics using the variable EJP_i provides information on the (lack of) capacity to generate employment in the economy.

3.2. Selection of case countries

This work is part of a comprehensive study of energy efficiency in the EU within the context of the EU project EUFORIE [58]. The study presented here comprises the 'EU22', which consists of the member countries of the European Union, with the exception of Cyprus, Denmark, Estonia, France, Luxembourg, Malta and Slovenia (because of lack of required data). In this paper, however, we focus only on the methodological aspects of the assessment of energy intensity, and for this purpose we singled out three countries, Bulgaria, Finland and Spain. We selected these countries because of their markedly different characteristics: Finland represents a wealthy country with an abundant endowment of natural resources, the exploitation and export of which demand considerable energy consumption. Spain represents an EU country with a limited endowment of natural resources and a fair level of economic development. Bulgaria only recently accessed to the EU and represents an economy that is still struggling to achieve a level of development close to the European average.

3.3. System description: hierarchical organization of relevant economic sectors and subsectors

Scaling across hierarchical levels of organization of a social-ecological system (such as the economy) requires a sound definition of the boundaries of the system and the (sub)compartments studied, as well as a semantic description of relevant functional relations among the different (sub)compartments and levels of
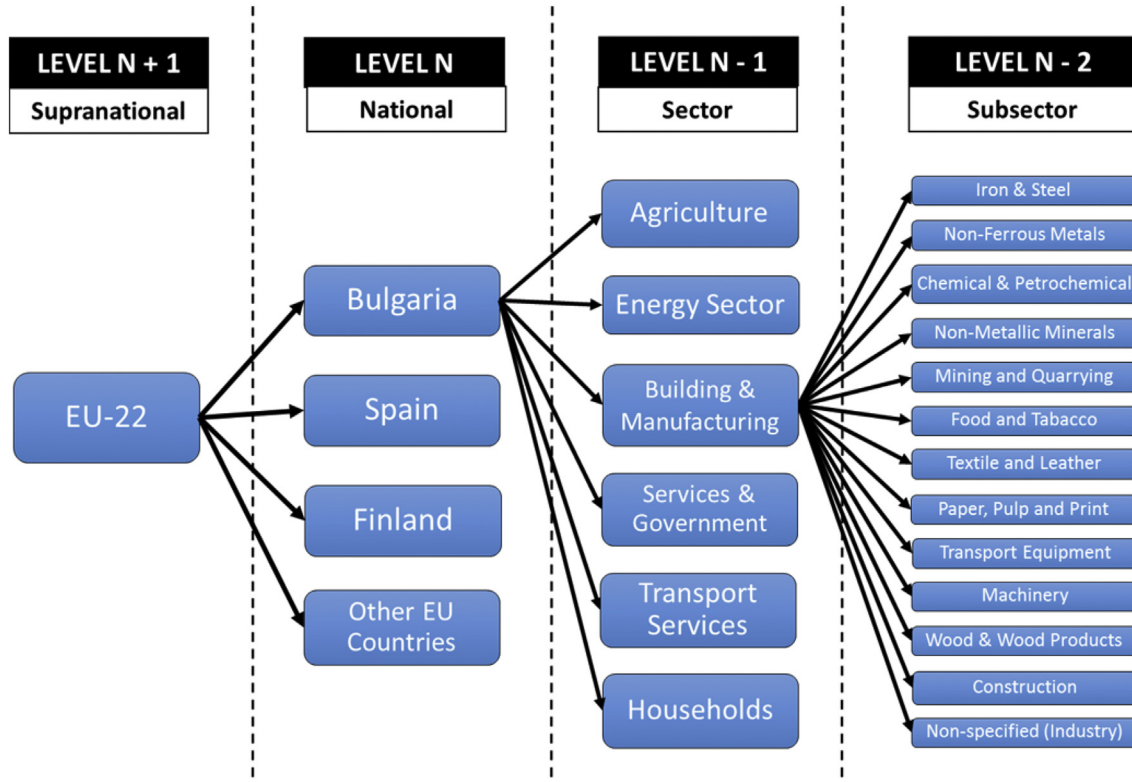
Fig. 3. Dendrogram illustrating the different hierarchical levels of analysis of a social-ecological system.

analysis. Criteria used in our study are:

1. The selected definition of the set of compartments (sectors or end-uses) must provide closure at all levels. This requires that the sum of the sizes of the parts equals the size of the total system (at all levels), and that the definition of the size of the parts is mutually exclusive (no double counting);
2. The data required to define both the size and the characteristics of individual compartments must be amenable to the data provided by the subdivisions practiced in national statistics.

As shown in Fig. 3, we select the national level as our focal level (level n). We then define within this 'whole' a set of lower-level compartments (economic sectors) at level (n-1) on the basis of the socio-economic functions expressed in a society, namely agricultural sector, energy sector,[1] industrial sector (or building & manufacturing following previous MuSIASEM literature), service & government, transport sector, and households (or residential sector). In accord with this categorization, the energy sector comprises the following activities: mining of coal and lignite; extraction of crude petroleum and natural gas; support activities for petroleum and natural gas extraction; manufacture of coke and refined petroleum products; electricity, gas, steam and air conditioning supply (that is, divisions no. 5, 6, 9.1, 19, 35 from NACE Rev.2).

In this work, we further subdivide the Building and Manufacturing sector (BM), alternatively called industrial sector, into various sub-sectors as shown in Fig. 3. In addition, we distinguish a supra-national level (level n+1), that is, the EU-22.

The definition of the industrial (or BM) sector and subsectors matches the Energy Balance Data [59] categorization of Eurostat (nrg_110a) for Industry: codes B_101 800 to B_101 853. Data on hours worked (human activity – HA) and value added (VA) have been obtained from the *Annual detailed enterprise statistics for industry* (sbs_na_ind_r2) [60] and *construction* (sbs_na_con_r2) [61] also provided by Eurostat (V16150 *Number of hours worked by employees* for HA and V12150: V*alue added at factor cost* for VA). These data have been aggregated bottom-up-wise as shown in Table 1 to match the industrial categorization from the Energy Balances following the NACE Rev. 2 classification as its metadata establish [62].

Note that the category of Mining and Quarrying in Table 1 only considers mining of metal ores and quarrying of raw material other than primary energy sources, as well as their supporting activities (NACE categories B7, B8 and B9.9). Mining of coal and lignite (B5), extraction of crude petroleum and natural gas (B6) and support activities for petroleum and natural gas extraction (B9.1) are included in the Energy Sector (ES).

3.4. Data array describing the metabolic characteristics of end-uses

We characterize the metabolic characteristics of end-use sectors using the following data array (defined in relation to quantities calculated on a year basis):
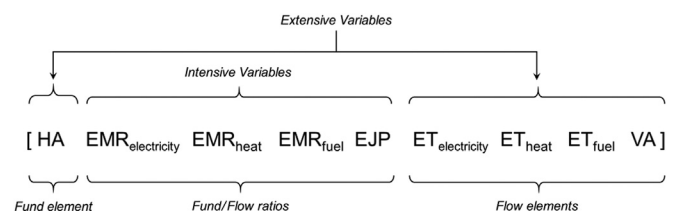
---

[1] Due to mining activity is split in this analysis, we change the nomenclature of previous studies referring to this sector as Energy and Mining. Mining for energy is allocated in the Energy Sector, whereas mining of non-energetic raw materials is allocated in the Mining and Quarrying, a subsector of the industrial sector.

Energy Balance Data Categorization (IEA & Eurostat)	Human Activity and Value Added Data Categorization (NACE Rev. 2 Divisions)
Iron and Steel	C24.1 - Manufacture of basic iron and steel and of ferro-alloys C24.2 - Manufacture of tubes, pipes, hollow profiles and related fittings, of steel C24.3 - Manufacture of other products of first processing of steel C24.5.1 - Casting of iron C24.5.2 - Casting of steel
Non-Ferrous Metals	C24.4 - Manufacture of basic precious and other non-ferrous metals C24.5.3 - Casting of light metals C24.5.4 - Casting of other non-ferrous metals
Chemical and Petrochemical	C20 - Manufacture of chemicals and chemical products C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations
Non-Metallic Minerals	C23 - Manufacture of other non-metallic mineral products
Mining and Quarrying	B7 - Mining of metal ores B8 - Other mining and quarrying B9.9 - Support activities for other mining and quarrying
Food and Tobacco	C10 - Manufacture of food products C11 - Manufacture of beverages C12 - Manufacture of tobacco products
Textile and Leather	C13 - Manufacture of textiles C14 - Manufacture of wearing apparel C15 - Manufacture of leather and related products
Paper, Pulp and Print	C17 - Manufacture of paper and paper products C18 - Printing and reproduction of recorded media
Transport Equipment	C29 - Manufacture of motor vehicles, trailers and semi-trailers C30 - Manufacture of other transport equipment
Machinery	C25 - Manufacture of fabricated metal products, except machinery and equipment C26 - Manufacture of computer, electronic and optical products C27 - Manufacture of electrical equipment C28 - Manufacture of machinery and equipment n.e.c.
Wood and Wood Products	C16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
Construction	F - Construction
Non-specified (Industry)	C22 - Manufacture of rubber and plastic products C31 - Manufacture of furniture C32 - Other manufacturing

Where.

- HA: Human activity allocated in the form of jobs to the end-use, measured in hours (h).
- ET_i: Amount of energy throughput metabolized in the form of energy carrier i by the end-use, where i is either electricity, heat or fuel, measured in joules (J);
- VA: Value added generated by the end-use, measured in euros (€);
- EMR_i–Energy Metabolic Rate: the amount of energy carrier i metabolized per hour of work allocated to the end-use, measured in joules of EC_i per hour (J/h);
- EJP–Economic Job Productivity: the value added (VA) at factor cost generated per hour of work allocated to the end-use, measured in euros per hour of work (€/h).

As observed earlier, the information in the data array is redundant (we can calculate the intensive variable by dividing the extensive variables by the fund element HA or calculate the extensive variables by multiplying the intensive variables by the fund element HA). However, it is exactly the redundancy in the information space created in this way that makes it possible the scaling between information organized in this way and referring to compartments organized within the hierarchical structure discussed so far.

In accordance with Georgescu-Roegen's flow-fund scheme [64], one of the pillars of MuSIASEM, human activity (HA) is defined as a fund element, whereas energy throughput (ETs) and value added (VA) are flow elements. All three are extensive variables characterizing the size (weight) of the end-use. Note that for each end-use, the throughput of the energy carriers (electricity, heat and fuel) are obtained by aggregating (bottom-up-wise) the different forms of each of these energy carriers provided in the Energy Balances of Eurostat [59], as shown in Table 2.

Dividing flow by fund elements, we obtain the intensive variables EMR and EJP. Energy metabolic rates (EMR_i) are calculated for each of the energy carriers: electricity, heat and fuel. As explained in section 2.2, this strategy permits to conserve valuable information about the quality and quantity of energy throughput in the form of different carriers metabolized in each end-use. The economic job productivity (EJP) represents the value added generated in a given end-use sector per hour of work required in that compartment. With the term 'economic *job* productivity' (rather than economic *labor* productivity used in previous MuSIASEM literature) we want to stress the qualitative aspect of human labor. Indeed, not all working hours are the same in the sense that they are complemented by different investment of energy carriers and technological capital in expressing their tasks. For this reason, in a more refined analysis (not presented here) it is possible to introduce different categories of jobs (e.g. high, medium, low level of instruction, experience, type of skills) in the same way as we have done for the categories of energy carriers (electricity, process heat and fuel).

Being intensive variables, EMR_i and EJP_i provide benchmark values; they describe the metabolic characteristics of a specific typology of end-use independently of its size. Therefore, EMR_i and EJP_i allow a comparison of the characteristics of analogous end-uses across countries, regions or sub-sectors with different sizes of the population and work force. For instance, we can compare the electricity throughput and value added per hour of work in the "textile and leather" sub-sector between Germany and Malta.

3.5. Data sources

Data on hours worked and gross value added are from National Accounts (NA) [65] for section 4.2 and Structural Business Statistics (SBS) for Sections 4.1 and 4.3 (value added at factor cost instead of gross value added in this case). Due to the different methodologies of collecting data in these two sources, comparison between the benchmarks of these sections are not possible. Data on the total population are from Eurostat (*Population on 1 January by age and sex*) [66]. Time allocation to the household sector is calculated as the difference between total time (based on total population) and time allocated to the paid work sector, Data on energy are from Eurostat Energy Balances [59]. Energy consumption in the household sector (section 4.2) has been calculated by adding residential consumption (from Energy Balance) and fuel consumption by private cars (hypothesis: 80% of all the fleet) and motorcycles (hypothesis: 90% of all the fleet) (data extracted from the Transport Sector). Fuel consumption has been calculated multiplying the kilometers per year done by vehicles on national territory [67] and the average fuel consumption [68] (taking into account the average age of the EU car fleet [69], the liters per ton and gross calorific

Table 2
Aggregation of the different forms of energy carriers reported in the Energy Balances of Eurostat [59].

Energy Carrier	Energy product	Eurostat code
Electricity	Electrical energy	6000
Heat	Hard coal and derivatives	2100
	Lignite and derivatives	2200
	Oil Shale and Oil Sands	2410
	Refinery gas	3214
	Ethane	3215
	Liquified petroleum gas (LPG)	3220
	Petroleum Coke	3285
	Gas	4000
	Solar thermal	5532
	Solid biofuels (excluding charcoal)	5541
	Biogas	5542
	Municipal waste (renewable)	55431
	Charcoal	5544
	Geothermal	5550
	Waste (non-renewable)	7200
Fuel	Gasoline (without biofuels)	3234
	Aviation Gasoline	3235
	Other Kerosene	3244
	Gasoline Type Jet Fuel	3246
	Kerosene type jet fuel (without biofuels)	3247
	Gas/diesel oil (without biofuels)	3260
	Total Fuel Oil	3270A
	Liquid biofuels	5545

value for gasoline and diesel fuels [70]; for motorcycles we assume a consumption of 5 L/100 km).

3.6. Data representation: normalized chromatic intensity

While keeping data disaggregated is essential to preserve valuable information (e.g., the distinction between different typologies of energy carriers), the consequent proliferation of data records represents a challenge for the visualization of the quantitative characterization. We therefore use Normalized Chromatic Intensity (NCI) to help the reader in quickly detecting patterns in the data through gradients in color *intensity*. The generation of NCI for intensive variables (EMRs and EJP) is obtained in three steps: first, identifying the maximum and minimum values for each indicator over the set of data; second, calculating the range of values for each indicator (difference between maximum and minimum value of the series); and third, assigning proportional intensities of color for the intermediate values in relation to its normalized distance to the extremes of the interval (maximum intensity of the color for maximum values and no-color for minimum values). In this way, we obtain a chromatic visualization of the differences helping pattern recognition and detection of outliers in the data set.

4. Results

In this section, we present the results of our analysis of the energy performance of the industrial sectors of Bulgaria, Finland and Spain. We remind the reader that the data only serve to validate the methodology, and that an exhaustive comparison of the energy performance of these countries is not a purpose of this study.

4.1. Energy performance of national industrial sectors in the European context

In Table 3 we show the energy performance of the industrial sector as a whole (level n-1) for Bulgaria, Finland and Spain using a data array characterizing the end uses of flows and fund elements in this sector. The energy performance of the industrial sector of the EU22 (the end use data array calculated at the level $n+1$) is also listed for reference. Scaling up national data to the EU22 level is useful to obtain more robust benchmark values for the industrial sector in the European context. To scale up, we sum the extensive variables (HA, ETs and VA) of the industrial sectors of all the nations making up the EU-22 and then obtain the corresponding ratios by dividing by the total HA_{BM} of EU-22 calculated summing together the HA_{BM} of the 22 economies. As a result, we obtain the data array shown in Table 3, [61 107 12] MJ/h and 33 €/h, which can be used to make internal comparisons. It can be used for comparison with the values for the national industrial sectors (inside Europe) or for external comparisons when considering analogous end-use matrix referring to economies operating in other world regions.

At this level of analysis, we can analyze the various national industrial sectors in relation to the EU industrial cluster (data arrays

Table 3
Metabolic characteristics of the industrial sector as a whole of Bulgaria, Finland, Spain, and the EU22. The economic energy intensity (EEI) is listed for comparison only.

2012	HA (10⁹ h/year)		EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)		ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	VA (10⁹€)	%HA_BM/ HA_BM_EU22	%VA_BM/ VA_BM_EU22	EEI (MJ/€)
Europe	54	X	61	107	12	33	=	3.304	5.766	660	1.763	100%	100%	15
Bulgaria	1,0		29	51	3,4	6,0		30	53	3,5	6,2	1,9%	0,35%	23
Finland	0,74	X	187	294	47	44	=	137	216	35	32	1,4%	1,8%	20
Spain	4,3		61	129	13	31		261	551	57	132	7,9%	7,5%	10

calculated at *n-1* versus *n+1* level) by looking at: (i) intensive variables (performance of the processes, unitary values), and (ii) extensive variables (considering the size of the processes). As shown in Table 3, the industrial sector of Bulgaria shows a poor performance within the European context with a vector of EMRs of [29 51 3,4] MJ/h and an EJP of only 6 €/h. The Spanish industrial sector displays a metabolic pattern that is similar to the average European benchmarks [61 129 13] MJ/h and 31 €/h, while Finland stands out well above the European average with [187 294 47] MJ/h and 44 €/h. Regarding size, we can deduct from Table 3 that the industrial sector of Spain is a significant contributor to the European industrial sector, both in terms of labor time (7,9%) and value added (7,5%). The Finland industry generate with less HA (1,4%) than Bulgaria (1,9%) more VA (1,8%) over Europe than Bulgaria (just 0,35%).

Table 3 also shows that looking only at the economic energy intensity (EEI) at this level can be misleading (energy consumption for calculating EEI is expressed in joules equivalent of gross energy requirement following the protocol of [9]). For instance, while the EEIs of Bulgaria and Finland are more or less the same (23 and 20 MJ/€ respectively), they display a markedly different metabolic pattern, with the energy throughputs and value added per hour of labor in the Finnish industry being significantly higher than in Bulgaria. As explained by Giampietro et al. [18] and Fiorito [29], at the level of the whole economy the EEI is a poor indicator because of the strong correlation between the total energy consumption and the GDP. For this reason, one can find clusters of countries with very similar values of EEI but completely different levels of technological efficiency [29]. In order to understand the relation between technological characteristics, economic performance and energy and carbon intensity we have to open the black-box and move to lower hierarchical levels of analysis.

4.2. Energy performance of the main economic sectors at the national level

In this section we examine the energy performance of the main economic sectors at the national level: the agricultural sector (AG), the energy sector (ES), the industrial sector (BM), the transport sector (TS), service and government (SG), and the household sector (HH). At this level, we can compare the performance of the various economic sectors within selected national economies, as well as selected economic sectors among the various national economies. As mentioned earlier, given the different methodology of collecting data on hours worked between National Accounts (NA) used in this section and Structural Business Statistics (SBS) used in the other sections, comparisons among values of EMR or ELP have to be done with caution (the mismatch of data may imply a difference of around 30%).

As can be seen from Tables 4–6, Bulgaria, Finland and Spain display a similar metabolic pattern: the energy sector has the highest metabolic rate of electricity (EMR_elec) and heat (EMR_heat),

whereas the transport sector has the highest metabolic rate of fuel (EMR_fuel). This is to be expected given that the energy sector (ES) is mainly powered by big machinery controlled by few hands (power plants, refineries, liquefaction and regasification plants, etc.), whereas the power capacity in the transport sector (TS) mainly consists in fuel converters (cars, motorcycles, trucks, airplanes) that require more human control.

Comparing metabolic patterns among countries, we clearly see that Finland is the country with the highest overall metabolic rates ([6,4 7,0 6,0] MJ/h) at the level of the entire society. A cross-country comparison among the metabolic rates of the household sectors (level n-1) can give us an indication of the relative material standard of living (levels of consumption at the household level, when outside work). Electricity (EMR_elec) and heat (EMR_heat) metabolic rates are the same (around 0,7 and 0,8 MJ/h, respectively) for Bulgaria and Spain, despite the colder winters in Bulgaria, but much higher for Finland (1,9 and 1,4 MJ/h, respectively). Different consumption of fuels (EMR_fuel) between Bulgaria and Spain (0,34 versus 1,1 MJ/h) may reflect less cars per capita (0,4 versus 0,5) and km/vehicle/year (3.500 versus 8.900) in Bulgaria than in Spain. The difference with Finland is even more marked (EMR_fuel = 2,8 MJ/h) with almost 0,6 cars per capita and more than 15,000 km/vehicle/ year [71]. Regarding the metabolic rates of the productive sectors, Finland has again the highest EMRs with the exception of EMRs values in TS and EMR_heat in ES and SG, suggesting that it has on average the highest levels of mechanization or technological capitalization in its economic sectors [18]. The transport sector of Bulgaria deserves special mention. It presents the highest EMR_heat (82 MJ/h) due to the big amount of natural gas consumed in pipeline transport [59].

As regards the economic job productivity (EJP)[2] the three countries present a similar metabolic pattern: the highest EJP is found in the energy sector followed by the industry and service & government sectors, and the transport sector. The agricultural sector exhibits the lowest economic job productivity. This metabolic pattern is consistent with the general pattern in Europe [18]. Finland presents the highest EJP in all sectors, surpassed by Spain only in the energy sector (145 versus 176 €/h). Bulgaria lags behind in all sectors and its economy shows low competitiveness when comparing its EJP values with those of Finland and Spain. The low EMR values in the Bulgarian economic sectors could explain this fact, assuming that EMRs are a proxy of mechanization. Nonetheless, this cannot explain why the EJPs of Spain and Finland are quite similar despite the EMRs of Finland being about 3 times those of Spain.

Understanding this difference requires us to open the 'black-box' of the industrial sector and examine the pattern of use of

---

[2] In this section, the VA (and therefore EJP) data is only comparable between economic sectors and not with other sections due to it is obtained from a different database that use another definition for it. Namely, for this section the EJP is calculated with the *Gross Value Added at basic prices* and *Total employment domestic concept* from the *Nacional Accounts* (nama_nace10) facilitated by Eurostat [75].

Table 4
The metabolic pattern of the main economic sectors of Bulgaria. Data refer to 2012.

Bulgaria 2012	HA (10⁹ h/year)	EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)	ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	GVA (10⁹ €)	%HA_sec/ HA_AS	%GVA_sec/ GVA_AS	EEI (MJ/€)
Average Society (AS)	64	1,9	2,3	1,7	0,6	122	147	112	36	100%	100%	18
Agriculture (AG)	0,97	1,0	1,4	5,8	2,0	0,97	1,4	5,6	1,9	1,5%	5,3%	6,1
Energy Sector (ES)	0,10	223	133	8,4	26	22	13	0,84	2,6	0,16%	7,1%	29
Building & Manufacturing (BM)	1,3	22	40	2,6	5,8	30	53	3,5	7,7	2,1%	21%	18
Transport (TS)	0,33	3,3	82	249	6,5	1,1	27	81	2,1	0,51%	5,9%	68
Services & Government (SG)	2,9	10	2,7	0	7,4	29	7,8	0,99	22	4,6%	60%	4,0
Household (HH)	59	0,67	0,77	0,34	0	39	45	20	0	91%	0%	-

Table 5
The metabolic pattern of the main economic sectors of Finland. Data refer to 2012.

Finland 2012	HA (10⁹ h/year)	EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)	ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	GVA (10⁹ €)	%HA_sec/ HA_AS	%GVA_sec/ GVA_AS	EEI (MJ/€)
Average Society (AS)	47	6,4	7,0	6,0	3,6	305	333	283	172	100%	100%	9,0
Agriculture (AG)	0,26	21,5	36	67	18	5,7	9,6	18	4,7	0,6%	2,7%	11
Energy Sector (ES)	0,037	387	1.142	58	145	14	43	2,2	5,4	0,1%	3,1%	16
Building & Manufacturing (BM)	0,97	142	223	35,8	41	137	216	35	40	2%	23%	16
Transport (TS)	0,26	10	1,9	367	34	2,7	0,50	96	8,9	0,6%	5,2%	16
Services & Government (SG)	2,7	24	1,9	4,5	43	64	4,9	12	114	5,6%	66%	1,7
Household (HH)	43	1,9	1,4	2,8	0	81	59	121	0	91%	0%	-

Table 6
The metabolic pattern of the main economic sectors of Spain. Data refer to 2012.

Spain 2012	HA (10⁹ h/year)	EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)	ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	GVA (10⁹ €)	%HA_sec/ HA_AS	%GVA_sec/ GVA_AS	EEI (MJ/€)
Average Society (AS)	410	2,2	3,1	4,0	2,3	914	1.275	1.625	954	100%	100%	6,3
Agriculture (AG)	1,5	9,9	21	47	16	14	31	68	24	0,36%	2,5%	6,9
Energy Sector (ES)	0,18	352	1.617	50	176	64	292	9,0	32	0,04%	3,3%	16
Building & Manufacturing (BM)	5,9	44	94	9,7	32	261	551	57	187	1,4%	20%	7,3
Transport (TS)	1,5	11	4,2	670	29	16	6,4	1.005	43	0,37%	4,5%	33
Services & Government (SG)	22	13	3,6	2,3	30	289	80	52	668	5,4%	70%	1,4
Household (HH)	379	0,71	0,83	1,1	0	270	315	434	0	92%	0%	-

energy at a lower level of analysis.

4.3. Energy performance of industrial (sub)sectors

In this section we examine the industrial sector in detail. To this purpose, we construct a matrix formed by 13 data arrays that characterizes the metabolic pattern of the various sub-sectors (end-uses) of each country (Tables 7–9). Structuring the data in this manner we can easily compare the metabolic performance among the various industrial subsectors (level *n-2*) making up the

Table 7
End-use matrix for the BM sector and its subsectors for Bulgaria, year 2012.

Bulgaria / 2012	HA (10⁶ h/year)		EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)		ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	VA (10⁹ €)	%HA_sector/HA_AS	%VA_sector/VA_AS	EEI (MJ/€)
All Industry (BM)	1.039	x	29	51	3	6	=	30	53	3,5	6,2	100%	100%	23
Iron and Steel	10		250	204	0	5		2,6	2,1	0	0,05	1,0%	0,8%	175
Non-Ferrous Metals	9,0		343	118	89	28		3,1	1,1	0,80	0,26	0,9%	4,1%	40
Chemical and Petrochemical	35		118	388	5	10		4,2	14	0,17	0,37	3,4%	5,9%	71
Non-Metallic Minerals	34		80	533	10	8		2,7	18	0,32	0,28	3,2%	4,5%	96
Mining and Quarrying	18		190	3	16	32		3,4	0,051	0,28	0,57	1,7%	9,1%	17
Food and Tobacco	156		25	33	3	6		3,9	5,1	0,49	0,95	15%	15%	17
Textile and Leather	211	x	6	4	1	3	=	1,4	0,81	0,21	0,60	20%	9,6%	7,9
Paper, Pulp and Print	29		44	256	7	6		1,3	7,5	0,20	0,19	2,8%	3,0%	64
Transport Equipment	29		14	10	0	6		0,40	0,29	0	0,17	2,8%	2,8%	7,9
Machinery	179		18	9	1	6		3,2	1,6	0,17	1,1	17%	17%	9,6
Wood and Wood Products	24		27	69	0	4		0,65	1,7	0	0,09	2,3%	1,4%	39
Construction	219		5	3	4	6		1,0	0,63	0,88	1,2	21%	20%	3,6
Non-specified Industry	85		22	7	0	5		1,9	0,62	0	0,39	8,2%	6,2%	15

industrial sector within each country. Thus, we obtain a better understanding of: (i) the size and the proportion of the subsectors/end-uses composing the industrial sector, and (ii) the metabolic rates characterizing each of these subsectors/end-uses. Indeed, looking at these tables we see important differences among industrial subsectors of a country not only between the EJPs generated by the various subsectors, but also among the EMRs both in quantitative (MJ/h) and qualitative terms (the mix of electricity, heat and fuel).

For example, in Table 7 we see that in Bulgaria 'mining and quarrying' generates the highest VA per hour of labor (32 €/h) and 'textile & leather' the lowest one (3 €/h). The two metallurgic subsectors, 'iron & steel' and 'non-ferrous metals', have the highest EMR_elec (250 and 343 MJ/h) but widely different EJPs (5 versus 28 €/h). This difference does not emerge from the corresponding economic energy intensities (175 versus 40).

Tables 7–9 clearly show that the energy intensity of the whole (the entire industrial sector–'All industry') is determined by two factors related to the parts: the relative size of the fund element human activity (i.e., labor time) allocated to the subsectors and the metabolic characteristics of the subsectors (the flow/fund ratios – EMRs and EJP). Considering only the economic energy intensity (EEI) of the industrial sector as whole, we would miss all the information provided in Tables 7–9. This information is essential for understanding the dependency of production processes on different forms of energy carriers, hours of labors and VA, as well as the relation among these factors.

In Tables 7–9 data organization facilitates a comparison among industrial subsectors within a country. In the alternative, we can also organize the data to facilitate a cross-country comparison of the metabolic performance of specific subsectors. This is illustrated in Table 10 for 'iron & steel' and in Table 11 for 'paper, pulp & print'. In this example of analysis, European benchmarks are used to highlight the variability in the performance of the specific subsector considered within the European context (level n-2 versus n+1).

As can be seen from Tables 10 and 11, the metabolic rates (EMR) of the same industrial subsector can differ widely among different countries in Europe. What is important in this analysis is that these differences cannot simply be attributed to different efficiencies of the technologies employed. Rather these differences are mostly due to location-specific conditions. For example, highly specific industrial processes (e.g., cutting massive quantities of trees to produce pulp) are often only possible in particular locations (e.g. where

large forests to be exploited are still available). These specific situations lead to specialization of tasks/processes at the international (e.g., EU) level. For instance, in the case of pulp and paper production –a process or sub-sub-sector that is extremely intensive in terms of electricity and heat consumption (MJ/h) (the most intensive of all industrial end-uses analyzed)– the availability of an abundant supply of wood is essential. Due to its favorable boundary conditions (cheap hydro-electricity and abundance of woods), Finland has a clear comparative advantage in this field and is the second producer of pulp (raw product in the subsector) in Europe with 10 million tonnes in 2012 (Sweden is top producer with 12 million tonnes and Germany a distant third with 3 million tonnes) [72]. Nonetheless, when considering the sub-sub-sector *paper and board* (finished product in the 'paper & pulp' subsector) Germany is the first largest producer, followed by Sweden and Finland (22, 11 and 11 million tonnes respectively) [72]. In fact, paper and board can be produced either from recycled paper and non-fibrous materials or from pulp. These two methods of production are quite different in terms of energy intensity (the kraft process is very energy intensive!). Hence if different countries rely on different mixes of production methods, the country relying on the most energy-demanding processes (e.g., pulp production in Finland) will exhibit the higher aggregate metabolic rate at the subsector level. However, when looking at these differences at this level of analysis it becomes clear that the different values observed depend on the specificity of the type of production (specialization) developed in the sub-sector and not on the *efficiency* of the technologies used in the process. In the same way, the characterization of the metabolic pattern of an industrial process can result completely irrelevant if that particular activity is extremely marginal in the national economy. This is for example the case with the production of pulp and paper in Italy, which relies entirely on import for covering its domestic consumption [72].

The analysis of the pulp and paper sub-sector clearly shows that any discussion over the issue of energy and carbon intensity of a country in relation to the efficiency of the technologies used in the economy should start from an analysis of the mix of economic activities carried out in the different sectors and the selective externalization of the most energy intensive economic activities by means of import/export of (semi-finished) products (factors 3 and 4 in Fig. 1). The mix of domestic production and the openness of the industrial sector are closely related and should be analyzed simultaneously. Moreover, in a globalized economy, none of these two factors is directly affected by local

Table 8
End-use matrix for the BM sector and its subsectors for Finland, year 2012.

Finland 2012	HA (10^6 h/year)		EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)		ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	VA (10^9 €)	%HA_sector/HA_AS	%VA_sector/VA_AS	EEI (MJ/€)
All Industry (BM)	735	x	187	294	47	44	=	137	216	35	32	100%	100%	20
Iron and Steel	18		664	1.658	308	33		12	30	5,6	0,60	2,5%	1,9%	120
Non-Ferrous Metals	5,4		1.251	313	152	69		6,7	1,7	0,82	0,37	0,7%	1,1%	56
Chemical and Petrochemical	26		663	402	47	96		17	10	1,2	2,5	3,5%	7,7%	23
Non-Metallic Minerals	24		117	290	36	45		2,8	7,0	0,87	1,1	3,3%	3,4%	15
Mining and Quarrying	8,4		576	33	175	69		4,8	0,28	1,5	0,58	1,1%	1,8%	26
Food and Tobacco	56		101	50	25	44		5,7	2,8	1,4	2,4	7,6%	7,6%	8,1
Textile and Leather	9,5	x	80	21	22	39	=	0,76	0,20	0,21	0,37	1,3%	1,1%	6,8
Paper, Pulp and Print	50		1.386	3.095	61	67		69	154	3,0	3,3	6,8%	10%	106
Transport Equipment	24		43	4,0	16	35		1,0	0,09	0,38	0,83	3,2%	2,6%	4,0
Machinery	212		36	3,3	3,2	38		7,7	0,69	0,67	8,0	29%	25%	2,7
Wood and Wood Products	34		212	222	19	32		7,1	7,5	0,63	1,1	4,6%	3,4%	25
Construction	231		6	0	66	41		1,3	0	15	9,4	31%	29%	2,6
Non-specified Industry	38		36	33	81	42		1,4	1,3	3,1	1,6	5,2%	5,0%	5,8

Table 9
End-use matrix for the BM sector and its subsectors for Spain, year 2012.

Spain 2012	HA (10^6 h/year)		EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)		ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	VA (10^9 €)	%HA_sector/HA_AS	%VA_sector/VA_AS	EEI (MJ/€)
All Industry (BM)	4.269	x	61	129	13	31	=	261	551	57	132	100%	100%	10
Iron and Steel	69		689	1.037	39	35		48	72	2,7	2,4	1,6%	1,8%	86
Non-Ferrous Metals	30		1.283	232	89	51		38	6,9	2,7	1,5	0,7%	1,1%	74
Chemical and Petrochemical	201		151	667	40	55		30	134	8,1	11	4,7%	8,3%	22
Non-Metallic Minerals	167		139	765	39	29		23	128	6,5	4,9	3,9%	3,7%	43
Mining and Quarrying	32		152	193	86	49		4,8	6,1	2,7	1,6	0,7%	1,2%	15
Food and Tobacco	603		57	72	15	32		34	43	9,2	20	14%	15%	7,6
Textile and Leather	188	x	38	34	15	20	=	7,2	6,4	2,9	3,8	4,4%	2,9%	7,8
Paper, Pulp and Print	174		107	313	26	32		19	55	4,5	5,7	4,1%	4,3%	20
Transport Equipment	286		33	20	12	39		10	5,8	3,3	11	6,7%	8,4%	3,2
Machinery	686		20	21	3,4	30		13	14	2,3	20	16%	15%	2,6
Wood and Wood Products	80		62	188	8	20		5,0	15	0,62	1,6	1,9%	1,2%	19
Construction	1.453		6	24	3	28		8,9	35	5,1	41	34%	31%	1,7
Non-specified Industry	300		66	102	21	28		20	31	6,3	8,3	7,0%	6,3%	11

Table 10
Metabolic pattern of the 'iron and steel' subsector for Bulgaria, Finland, Spain and the EU-22, year 2012.

Iron and Steel 2012	HA (10^9 h/year)		EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)		ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	VA (10^9 €)	%HA_sector/HA_EU_AS	%VA_sector/VA_EU_AS	EEI (MJ/€)
Europe (Average Sector)	974	x	408	1523	34	35	=	397	1.484	33	34	1,8%	1,9%	80
Bulgaria	10		250	204	0	5,0		2,6	2,1	0	0,052	1,0%	0,8%	175
Finland	18	x	664	1.658	308	33	=	12	30	5,6	0,60	2,5%	1,9%	120
Spain	69		689	1.037	39	35		48	72	2,7	2,4	1,6%	1,8%	86

Table 11
Metabolic pattern of the 'paper, pulp and print' subsector for Bulgaria, Finland, Spain and EU-22, year 2012.

Paper, Pulp and Print 2012	HA (10^9 h/year)		EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)		ET_elec (PJ/year)	ET_heat (PJ/year)	ET_fuel (PJ/year)	VA (10^9 €)	%HA_sector/HA_EU_AS	%VA_sector/VA_EU_AS	EEI (MJ/€)
Europe (Average Sector)	1.937	x	218	391	15	34	=	422	757	29	66	3,6%	3,8%	30
Bulgaria	29		44	256	7	6,3		1,3	7,5	0,20	0,19	2,8%	3,0%	64
Finland	50	x	1.386	3.095	61	67	=	69	154	3,0	3,3	6,8%	10%	106
Spain	174		107	313	26	32		19	55	4,5	5,7	4,1%	4,3%	20

consumption patterns! This is an important point to consider in the evaluation of policies regarding the reduction of energy and carbon intensity.

5. Conclusions

A better understanding of how energy use is related to the

functioning and the size of the economy and the use of other production factors (e.g., labor) is paramount for evaluation of energy policies. Consider the following questions: Is the EU 20% energy efficiency target by 2020 [73] achievable? What has to be changed in the actual pattern of energy use in the industrial sector to achieve this goal? What would be the cost (or better, the consequence) of achieving this target? We firmly believe that available quantitative analyses of the energy (carbon) intensity of the economy do not provide the information required for answering these questions and hence that at present energy policies are made on the basis of wishful thinking.

Ours is an attempt to characterize the energy performance of the industrial sector across hierarchical levels of organization by exploring the complex set of relations between energy consumption, requirement of human activity and value added generation. Our analysis characterizes the quantitative (size) and qualitative (rates/intensities of flows) energy metabolic characteristics of the various sub-sectors and sub-sub-sectors of the industrial sector, with the economic job productivity (€/hour of labor) flagging the expected pattern of externalization. A key feature of our approach is the end-uses data array composed of extensive and intensive variables. The use of this data array facilitates the extension of the analysis to include additional resources (e.g., water, land use, technological capital) and sink-side impacts (emissions, discharges) (see Ref. [48] for an application to the water-energy-food nexus).

All the same, the analysis carried out at the level of the industrial sub-sector still leaves out important aspects as the end-uses data array at this level may refer to end-uses that are still qualitatively very different (steel can be produced from scrap or ores, paper from wood/pulp or recycled paper). Indeed, it would be important to move further down to a still lower level of analysis—that of production processes carried out at the level of sub-sub-sectors—in order to describe the end-uses in terms of technical coefficients (or biophysical production functions) that refer to homogenous typologies of processes. In this way, the level of analysis can reach a point in which one establishes a bridge between bottom-up information (expected characteristics of specific technologies) and top-down information (statistical data referring to the categories provided by statistical offices). The proposed method of accounting would then become a powerful complement—offering the biophysical perspective—of the aggregate production function in neoclassical economics. The information provided by production functions described in macroeconomics analysis could be scaled down tracking the biophysical roots of the economic process across levels. This integration would avoid some of the problems associated with the excessive reliance on neo-classical economic tools [74].

Unfortunately, the inclusion of lower levels of analysis beyond the industrial subsector is currently still problematic as it requires a better definition of the categories of accounting (hierarchical structure of the industrial sector) by the various statistical offices. Statistical offices should make a joint effort to offer energy balances, trade, and labor data using a uniform classification of all economic activities (e.g., NACE Rev 2) so that assessments of the consumption of energy carriers, hours of human activity (in different types of jobs), and monetary indicators match with each other at all levels of analysis, thus avoiding the comparison of apples with oranges in the same category of accounting.

Acknowledgements

References

[1] European Commission. Energy 2020: a strategy for competitive, sustainable and secure energy, vol. 639; 2010. Brussels.
[2] Congressional Research Service, Leggett JA. President Obama's climate action plan. 2014.
[3] Milman O. Trump's alarming environmental rollback: what's been scrapped so far. The Guardian. 2017. https://www.theguardian.com/environment/2017/jul/04/trump-emvironmental-rollback-epa-scrap-regulations.
[4] Patterson MGMG. What is energy efficiency? Concepts, indicators and methodological issues. Energy Pol 1996;24:377–90. https://doi.org/10.1016/0301-4215(96)00017-1.
[5] Phylipsen GJM, Blok K, Worrell E. International comparisons of energy efficiency-Methodologies for the manufacturing industry. Energy Pol 1997;25: 715–25. https://doi.org/10.1016/S0301-4215(97)00063-3.
[6] Lutzenhiser L. Through the energy efficiency looking glass. Energy Res Soc Sci 2014;1:141–51. https://doi.org/10.1016/j.erss.2014.03.011.
[7] Shove E. What is wrong with energy efficiency? Build Res Inf 2017;0:1–11. https://doi.org/10.1080/09613218.2017.1361746.
[8] Rodgers DT. Atlantic Crossings. Social politics in a progressive age. Harvard University Press; 1998.
[9] Labanca N, Bertoldi P. Beyond energy efficiency and individual behaviours: policy insights from social practice theories. Energy Policy 2018;115: 494–502. https://doi.org/10.1016/j.enpol.2018.01.027.
[10] Alexander JK. The mantra of efficiency. From waterwheel to social control. Baltimore: The Johns Hopkins University Press; 2008.
[11] Carnot S. Reflections on the motive power of fire, and on machines fitted to develop that power. New York: John Wiley & Sons; 1897.
[12] Maddox KP. Energy analysis and resource substitution. In: Roberts F, editor. Symp. Pap. Model. Net energy anal. Color. Springs, August 21-25, 1978. Chicago: Institute of Gas Technology; 1978. p. 133–44.
[13] Chapman PF. Energy costs: a review of methods. Energy Pol 1974;2:91–103.
[14] Leach G. Net energy analysis - is it any use? Energy Pol 1975;3:332–44. https://doi.org/10.1016/0301-4215(75)90041-5.
[15] Herendeen RA. Energy analysis of two technologies: gasohol and solar satellite power station. In: Roberts F, editor. Symp. Pap. Energy model. Net energy anal. Springs, August 21-25, 1978. Chicago: Institute of Gas Technology; 1978. p. 145–59.
[16] Fraley DW, McDonald CL. Issues in net energy analysis. Energy Model. In: Net energy anal. Symp. Pap. Inst. Gas technol. Color. Springs, CO; 1978. p. 161–81.
[17] IFIAS (International Federation of Institutes for Advanced Study). Energy analysis. Workshop on Methodology and Conventions. Report No.6. Stockhom: IFIAS; 1974. p. 89.
[18] Giampietro M, Mayumi K, Sorman A. The metabolic pattern of societies: where economists fall short. New York: Routledge; 2012.
[19] Liu XQ, Ang BW, Ong HL. Interfuel substitution and decomposition of changes in industrial energy consumption. Energy 1992;17:689–96. https://doi.org/10.1016/0360-5442(92)90076-C.
[20] Renshaw EF. Energy efficiency and the slump in labour productivity in the USA. Energy Econ 1981;3:36–42. https://doi.org/10.1016/0140-9883(81)90005-0.
[21] Jenne C a, Cattell RK. Structural change and energy efficiency in industry. Energy Econ 1983;5:114–23. https://doi.org/10.1016/0140-9883(83)90018-X.
[22] Cai W, Liu F, Xie J, Liu P, Tuo J. A tool for assessing the energy demand and efficiency of machining systems: energy benchmarking. Energy 2017;138: 332–47. https://doi.org/10.1016/j.energy.2017.07.039.
[23] Jayal AD, Badurdeen F, Dillon OW, Jawahir IS. Sustainable manufacturing: modeling and optimization challenges at the product, process and system levels. CIRP J Manuf Sci Technol 2010;2:144–52. https://doi.org/10.1016/j.cirpj.2010.03.006.
[24] Lin T-Y, Chiu S-H, Yang H. Sustainable performance of taiwanese manufacturing industries over the past decade (2006-2015). Int J Autom Smart Technol 2017;7:141–6. https://doi.org/10.5875/ausmt.v7i4.1658.
[25] Wang Q, Liu F, Wang X. Multi-objective optimization of machining parameters considering energy consumption. Int J Adv Manuf Technol 2014;71: 1133–42. https://doi.org/10.1007/s00170-013-5547-z.
[26] Mahapatra K, Alm R, Hallgren R, Bischoff L, Tuglu N, Kuai L, et al. A behavioral change-based approach to energy efficiency in a manufacturing plant. Energy Effic 2017:1–14. https://doi.org/10.1007/s12053-017-9581-9.
[27] Edgar TF, Pistikopoulos EN. Smart manufacturing and energy systems. Comput

Chem Eng 2017. https://doi.org/10.1016/j.compchemeng.2017.10.027.

[28] Li X, Yao X. Multi-scale statistical process monitoring in machining. IEEE Trans Ind Electron 2005;52:924–7. https://doi.org/10.1109/TIE.2005.847580.

[29] Fiorito G. Can we use the energy intensity indicator to study "decoupling" in modern economies? J Clean Prod 2013;47:465–73. https://doi.org/10.1016/j.jclepro.2012.12.031.

[30] Polimeni JM, Mayumi K, Giampietro M, Alcott B. The Jevons paradox and the myth of resource efficiency improvements. London: Earthscan; 2008.

[31] Wang Z, Zhu H, Ding Y, Zhu T, Zhu N, Tian Z. Energy efficiency evaluation of key energy consumption sectors in China based on a macro-evaluating system. Energy 2018;153:65–79. https://doi.org/10.1016/j.energy.2018.04.009.

[32] Ang BW, Goh T. Bridging the gap between energy-to-GDP ratio and composite energy intensity index. Energy Pol 2018;119:105–12. https://doi.org/10.1016/j.enpol.2018.04.038.

[33] Moreau V, Vuille F. Decoupling energy use and economic growth: counter evidence from structural effects and embodied energy in trade. Appl Energy 2018;215:54–62. https://doi.org/10.1016/j.apenergy.2018.01.044.

[34] Eurostat. Energy balance sheets, vol. 33; 2016. https://doi.org/10.2785/52802.

[35] Mayumi K. The origins of ecological economics: the bioeconomics of georgescu-roegen. London and New York: Routledge; 2001.

[36] EJOLT. Environmental justice atlas. 2017. https://ejatlas.org. [Accessed 15 January 2017].

[37] Hall CAS, Klitgaard KA. Energy and the wealth of nations. Understanding the biophysical economy. New York: Springer; 2012.

[38] Smil V. Oil. A Beginner's guide. Oxford: Oneworld Publications; 2008.

[39] Guevara Z, Domingos T. The multi-factor energy input – output model. Energy Econ 2017;61:261–9. https://doi.org/10.1016/j.eneco.2016.11.020.

[40] Giampietro M, Mayumi K, Sorman AH. Energy analysis for a sustainable future: multi-scale integrated analysis of societal and ecosystem metabolism. New York: Routledge; 2013.

[41] OECD/IEA. World energy statistics 2016 database (1970–2016). IEA statistics; 2016.

[42] Eurostat International Trade in goods. 2017.

[43] Serrenho AC, Sousa T, Warr B, Ayres RU, Domingos T. Decomposition of useful work intensity: The EU (European Union)- 15 countries from 1960 to 2009. Energy 2014;76:704–15. https://doi.org/10.1016/j.energy.2014.08.068.

[44] McKinsey Global Institute. Debt and (not much) deleveraging. 2015.

[45] Georgescu-Roegen N. The entropy law and the economic process. 1971st ed. Cambridge, Massachusetts: Hardvard University Press; 1971.

[46] Velasco Fernández R, Ramos Martín J, Giampietro M. The energy metabolism of China and India between 1971 and 2010: Studying the bifurcation. Renew Sustain Energy Rev 2015;41:1052–66. https://doi.org/10.1016/j.rser.2014.08.065.

[47] Silva-Macher JC, Farrell KN. The flow/fund model of Conga: exploring the anatomy of environmental conflicts at the Andes–Amazon commodity frontier. Environ Dev Sustain 2014;16:747–68. https://doi.org/10.1007/s10668-013-9488-3.

[48] Giampietro M, Aspinall RJ, Ramos-martin J, Bukkens SGF, Sandra GF. Resource accounting for sustainability assessment: the nexus between energy, food, water and land use. New York: Routledge; 2014. https://doi.org/10.4324/9781315866895.

[49] Giampietro M, Mayumi K. Multiple-scale integrated assesment of societal metabolism: introducing the approach. Popul Environ 2000;22:109–53. https://doi.org/10.1023/A:1026691623300.

[50] Giampietro M, Mayumi K. Multiple-scale integrated assessments of societal metabolism: integrating biophysical and economic representations across scales. Popul Environ 2000;22:155–210. https://doi.org/10.1023/A:1026643707370.

[51] Pastore G, Giampietro M, Mayumi K. Societal metabolism and multiple-scale integrated assesment: empirical validation and examples of application. Popul Environ 2000;22:211–54. https://doi.org/10.1023/A:1026695724208.

[52] Giampietro M, Sorman AH. Are energy statistics useful for making energy scenarios? Energy 2012;37:5–17. https://doi.org/10.1016/j.energy.2011.08.038.

[53] Lotka AJ. Contribution to the energetics of evolution. Proc Natl Acad Sci U S A 1922;8:147–51. https://doi.org/10.1073/pnas.8.6.147.

[54] Odum HT, Pinkerton RC. Time's speed regulator: the optimum efficiency for maximum power output in physical and biological systems. Am Sci 1955;43:331–43.

[55] Prigogine I. Introduction to thermodynamics of irreversible processes. 2nd revise. New York: Interscience Publishers; 1961.

[56] Glansdorff P, Prigogine I. Thermodynamic theory of structure, stability and fluctuations. 1971. p. 306. https://doi.org/10.1119/1.1987158.

[57] Gualteri T. Europa hunde su propio acero. El País. 2015. http://economia.elpais.com/economia/2015/02/20/actualidad/1424434695_548626.html. [Accessed 21 March 2018].

[58] European Futures for Energy Efficiency (EUFORIE). Horizon2020 research and innovation programme. 2015. http://cordis.europa.eu/project/rcn/194572_en.html. [Accessed 27 January 2017].

[59] Eurostat. Energy balances. 2015. http://ec.europa.eu/eurostat/web/energy/data/energy-balances. [Accessed 21 October 2015].

[60] Eurostat. Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E). 2015. http://ec.europa.eu/eurostat/web/products-datasets/-/sbs_na_ind_r2. [Accessed 10 October 2015].

[61] Eurostat. Annual detailed enterprise statistics for construction (NACE Rev. 2, F). 2015. http://ec.europa.eu/eurostat/web/products-datasets/-/sbs_na_con_r2. [Accessed 10 October 2015].

[62] Eurostat. Statistical classification of economic activities in the European Community. NACE Rev 2008;2.

[63] Eurostat, European Commission. Energy statistics of the European Union: concepts and definitions on all flows ("aggregates") and products used in the Energy Statistics on quantities. Luxemburg; 2015.

[64] Georgescu-Roegen N. Energy and economic myths. South Econ J 1975;41:347–81. https://doi.org/10.2307/1056148.

[65] Eurostat. National Accounts employment data by industry (up to NACE A*64), 2015. http://ec.europa.eu/eurostat/web/products-datasets/-/nama_10_a64_e (accessed September 1, 2016).

[66] Eurostat. Population on 1 January by age and sex, 2015. http://ec.europa.eu/eurostat/web/products-datasets/-/demo_pjan (accessed September 1, 2016).

[67] Eurostat. Motor vehicle movements on national territory, by vehicles registration. 2012. http://ec.europa.eu/eurostat/web/products-datasets/-/road_tf_vehmov.

[68] The International Council on Clean Transportation (ICCT). European vehicle market statistics. 2016.

[69] European Automobile Manufacturers Association. Average vehicle age. 2017. http://www.acea.be/statistics/tag/category/average-vehicle-age.

[70] OECD/IEA. Energy statistics manual. 2005. https://doi.org/10.1787/9789264033986-en.

[71] Eurostat. Stock of vehicles by category and NUTS 2 regions [tran_r_vehst]. 2015. http://ec.europa.eu/eurostat/statistics-explained/index.php/Stock_of_vehicles_at_regional_level. [Accessed 1 October 2016].

[72] CEPI. Key statistics 2012 - confederation european pulp and paper industry. 2012. Brussels.

[73] European Parliament. Directive 2012/27/EU of the european parliament and of the council of 25 october 2012 on energy efficiency. Off J Eur Union Dir; 2012. p. 1–56. https://doi.org/10.3000/19770677.L_2012.315.eng.

[74] Daly HE. Georgescu-Roegen versus Solow/Stiglitz. Ecol Econ 1997;22:261–6. https://doi.org/10.1016/S0921-8009(97)00080-3.

[75] Eurostat. National Accounts by 10 branches - aggregates at current prices. 2015. http://ec.europa.eu/eurostat/web/products-datasets/-/nama_nace10_c. [Accessed 10 November 2015].