ARTICLE IN PRESS

Energy Policy xxx (xxxx) xxx

Contents lists available at ScienceDirect

Energy Policy

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

Fallacies of energy efficiency indicators: Recognizing the complexity of the metabolic pattern of the economy

Raúl Velasco-Fernández [a], Tessa Dunlop [b], Mario Giampietro [a,c,*]

[a] Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, 08193, Bellaterra, Spain
[b] European Commission, Directorate-General Joint Research Centre, Unit I.02 Foresight, Behavioural Insight and Design for Policy, Via E. Fermi, 2749, IT-21027, Ispra, VA, Italy
[c] Institució Catalana de Recerca i Estudis Avançats (ICREA), Passeig Lluis Companys 23, 08010, Barcelona, Spain

ARTICLE INFO

Keywords:
Energy efficiency
Energy performance
End-use matrix
Energy policy
Jevons paradox
Metabolic pattern

ABSTRACT

The strategy of energy efficiency to save energy is deceptively simple: the idea is to use less input for the highest amount of useful output. However, on a practical and conceptual level, efficiency is an ambiguous and problematic concept to implement. Of particular concern is the lack of contextual and qualitative information provided in energy efficiency measurements based on simple ratios. Oversimplification of efficiency measurements can have a detrimental effect on the choice of energy policies. Efficiency measurements are particularly problematic on a macroeconomic scale where a significant amount of meaningful information is lost through the aggregation of data into a simple ratio (economic energy intensity). First, practical examples are presented flagging conceptual problems with energy efficiency indicators, then an alternative accounting method—the end-use matrix—based on the concept of the metabolic pattern of social-ecological systems is illustrated to show the possibility of enriching efficiency indicators by adding qualitative and contextual information across multiple scales and dimensions. This method unpacks and structures salient energy input and output information in a meaningful and transparent way by generating a rich multi-level and multi-dimensional information space.

1. Introduction

Efficiency has become a central pillar of energy policy in industrialized nations globally. Energy efficiency is a policy priority in Europe having the goal to secure renewable and sustainable energy supply, by reducing greenhouse gas (GHG) emissions, saving costs and encouraging economic competitiveness. At the time of writing, the European Commission had announced a political agreement on new rules for improving energy efficiency as part of the Energy Efficiency Directive (EED) 2012/27/EU (European Parliament, 2012) adopted in 2012 and broader Clean Energy Package adopted in 2016 (European Comission, 2016). The new regulatory framework includes an energy efficiency target for the European Union (EU) for 2030 of 32.5% with an upwards revision clause by 2023 (European Commission, 2016).

However, little academic attention has been paid to the practical and conceptual problems related to the implementation of energy efficiency concepts and strategies (Ayres and Warr, 2005; Fiorito, 2013; Giampietro and Mayumi, 2008; Herring and Sorrell, 2009; Inhaber, 1997; Labanca and Bertoldi, 2018; Lutzenhiser, 2014; M. G. M. G. Patterson, 1996; Phylipsen et al., 1997; Shove, 2017). In a paper entitled "What is energy efficiency?" Murray Patterson (1996, p. 377) states:

> "Despite the continuing policy interest and the very many reports and books written on the topic of 'energy efficiency', little attention has been given to precisely defining the term … in general, energy efficiency refers to using *less energy* to produce *the same amount of services or useful output.*"

Indeed, semantic concepts such as 'advantages of using less energy input' or 'usefulness of the output' are difficult to quantify. Even 'the' guru of the quantification of the concept of efficiency —Sadi Carnot himself—warned the reader in the closing paragraph of his seminal book "Reflections on the Motive Power of Fire, and on Machines Fitted to Develop that Power" (Carnot, 1897) about the limited usefulness of a measurement of efficiency based on a simple output/input ratio:

> "We should not expect ever to utilize in practice all the motive power of combustibles. The attempts made to attain this result would be far

* Corresponding author. Institute of Environmental Science and Technology (ICTA), Autonomous University of Barcelona (UAB), ICTA-ICP (Edifici Z) Z/103, Carrer de les Columnes (Campus UAB), Cerdanyola del Vallès, 08193, Barcelona, Spain.
E-mail addresses: raul.velasco@uab.cat (R. Velasco-Fernández), mario.giampietro@uab.cat (M. Giampietro).

https://doi.org/10.1016/j.enpol.2019.111089
Received 20 January 2019; Received in revised form 8 October 2019; Accepted 1 November 2019

Abbreviations

AG	agriculture, forestry and fishing sector
EEI	economic energy intensity
EJP	economic job productivity
EM	energy & mining sub-sector
EMR	energy metabolic rate
ET	energy throughput
EU	European Union
EUM	end-use matrix
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
GVA	gross value added
h	hour
HA	human activity
HH	household or residential sector
J	joule
kWh	kilowatt-hour
m^3	cubic meter
MC	manufacturing and construction sector
MJ	megajoule
p.c.	per capita
PJ	petajoule
SG	services and government sector
USA	United States of America
USD	US Dollar

more harmful than useful if they caused other important considerations to be neglected. The economy [*efficiency*] of the combustible is only one of the conditions to be fulfilled in heat-engines. In many cases it is only secondary. It should often give precedence to safety, to strength, to the durability of the engine, to the small space which it must occupy, to small cost of installation, etc." [p. 59, italics added for emphasis].

As suggested by Carnot, the complexity of the performance of an energy system requires a combination of a variety of indicators (a multi-criteria performance space) and not just a single one (e.g., a single output/input ratio). Moreover, if it is unwise to assess the performance of an engine with a single efficiency indicator, it will be even more so for the performance of larger and more complex systems using energy, such as economic sectors or the entire economy.

The discussion on how to properly assess the performance of an energy system is crucial when assessing the utility of renewable energy innovations. For instance, according to the report of the Supreme Court of Auditing of Germany, the *Energiewende* represents a lesson of poorly informed policy (Bundesrechnungshof, 2016). Indeed, the significant economic investments in alternative energy sources in Germany led to high electricity prices without reducing emissions levels (Scholz et al., 2014). The generalized problems currently experienced with the integration of intermittent electricity sources in the grid are easily explained by the excessive simplifications adopted in the economic analyses used to inform policy (Renner and Giampietro, 2020).

Despite the challenges related to its quantification, the ambiguity of the term 'efficiency' has likely contributed to its success in cultural, scientific and political contexts (Alexander, 2008; Price, 1995). Often, the adjective 'efficient' is vague and used synonymously with 'better'. In this sense, it can be applied to many different contexts including efficient buildings, efficient cities, work practices, industrial processes and machines. But often little regard is paid to the implications of the pre-analytical decisions required to measure efficiency. When dealing with processes or systems operating across different scales, we can find trade-offs in efficiency changes and improvements when considering the same dimension of analysis (e.g., reducing electricity consumption per hour can increase the consumption per year), or among different relevant dimensions of performance (e.g., reducing energy use may increase labor demand).

Elizabeth Shove (2017, p. 1) notes that the positive connotations of efficiency are often left unquestioned:

"National and international responses to climate change are dominated by policies that promote energy efficiency and by people who take this to be a self-evidently important thing to do".

The use of efficiency as an indicator of performance creates an illusion that the information is 'scientifically sound' and that it is possible to measure overall energy performance in a simple target (Alexander, 2008; Rodgers, 1998). This may explain why policy discussions and recommendations tend to rely heavily on the concept of efficiency to establish normative targets, even though indicators generally use either energy consumption indicators or energy intensity metrics, especially in the EU. But seemingly crisp and concise, energy efficiency indicators often omit information necessary to undertake well-informed policy decisions. Instead, these authors recommend using the concept of 'energy performance' because the term can be associated with a more specific and well-defined characterization of the efficacy of complex energy processes. Energy performance is a more pertinent concept that can address the needs of social actors and policymakers to identify the factors relevant for making well-informed decisions regarding energy policy. On the other hand, this concept implies that it is impossible to define 'once and for all' how to measure energy efficiency, because the measure is instrumental and context-dependent. Instead, the concept of performance allows for a more nuanced and granular analysis of energy use that goes beyond the simplified output/input ratio. In other words, a more advanced accounting methodology can generate a valuable information space that describes the relations of multiple relevant energy attributes while respecting the co-existence of legitimate but contrasting definitions of what should be considered as an improvement. This information space is flexible in such a way as to integrate different indicators to analyze depending on the chosen research frame or inquiry.

The rest of the paper is organized as follows. Section 2 outlines the conceptual problems regarding the measurement of energy efficiency. Section 3 illustrates the technical and practical challenges in applying the concept of efficiency to complex macroeconomic systems. Section 4 presents two practical examples of the importance of considering the context with regard to generating efficiency measurements. Section 5 flags the conceptual challenges of input/output tables used for measuring energy efficiency. Section 6 outlines a potential 'solution' to the problem: the energy End-Use Matrix (EUM), a multi-level and multi-dimensional accounting scheme, based on the concept of metabolic pattern of social-ecological systems, that integrates relevant data across different dimensions (economic and biophysical indicators) and scales of analysis. Examples are presented to illustrate how the matrix addresses the methodological challenges associated with the simplification of energy efficiency data by providing a complex and detailed information space that allows a richer analysis of the energy performance of modern economies. Section 7 concludes.

2. Conceptual and methodological problems regarding the quantification of efficiency

The conceptual problems related to the quantification of energy transformations—i.e. the truncation problem, the join production dilemma and challenge of how to handle discrepancies in energy quality—have received ample attention in the past [see, for example, (Bullard and Herendeen, 1975; Chapman, 1974; Herendeen, 1981; IFIAS (International Federation of Institutes for Advanced Study), 1974; Leach, 1975; Maddox, 1978); for an overview (Giampietro et al., 2013)]. However, these insights appear to have been forgotten in recent times (Giampietro et al., 2013; Giampietro and Sorman, 2012).

Just as science and quantification cannot be considered free of human values and perceptions (Funtowicz and Ravetz, 1990), neither can the concept of energy efficiency (Boulding, 1981; Giampietro and Pimentel, 1992, 1991; M. G. M. G. Patterson, 1996; Shove, 2017). At its most basic level, energy efficiency is understood to be the ratio of an energy input used to create the greatest useful output. Yet the calculation of this ratio entails several methodological challenges: How does one decide how to define what 'energy input' (determining the cons of the process) and 'energy output' (determining the pros of the process) are in quantitative terms? The definition of 'energy input' requires a pre-analytical definition of a reference form of energy (e.g. mechanical, thermal, primary energy, secondary energy, peak or intermittent electricity) to be quantified. But this is still insufficient for a useful characterization: the energy input must be produced or used by some technical device with a given power capacity (this is needed to guarantee a given rate in time of the energy transformation). Moreover, to ensure that the output will render a useful result the requirement of human control for technical transformations must be considered (the coupling of hours of labor to the energetic transformation). Thus, when it comes to characterizing energy end-uses, a simple quantification of the quantity of 'energy input' that is transformed to generate the final end-use is insufficient to characterize 'the cons of the input'.

A central methodological challenge when assessing the quantity and utility of an energy input is that of aggregating incomparable energy qualities. For example, the residential sector uses both electricity and thermal carriers (e.g. natural gas) for its operations, but these two quantities cannot be easily compared based on the requirements of primary energy sources (this depends on the mix of PES used to produce electricity) (Giampietro and Sorman, 2012). The issue is complicated further when considering the implications of the concomitant requirement of power level and human labor. What if a reduction of 'energy input' can be obtained, but only at the cost of significantly reducing the rate of production of the output or significantly increasing the requirement of human labor? If efficiency and power are contrasting attributes of performance in a car, then can we say that a slower car is more fuel-efficient than a fast one?

This question points to the even more elusive definition of a 'useful output' of energy. The adjective 'useful' implies the need to assign human values and value judgments in order to define what is considered useful. In relation to this task, 'usefulness' has always been associated with the concept of 'energy service' (Fell, 2017) that a given input of energy helps to deliver. However, standard definitions of 'energy services' still do not measure the value of the 'output' in terms of practical end-uses (Fell, 2017). An indicator of the technical efficiency of 'lighting' cannot detect whether the lighting is taking place in an empty room.

Thus, quantities of 'energy' can only be defined and measured after establishing taxonomies of accounting categories reflecting different logical criteria (Giampietro et al., 2013). Examples of different logical criteria of accounting are:

i Endosomatic versus exosomatic energy (Georgescu-Roegen, 1971; Lotka, 1925): Endosomatic refers to the conversion of energy inputs used (converted) by the human body (food energy), while exosomatic refers to the conversion of energy inputs used (converted) by machines (i.e., gasoline or electricity). Indeed, when analyzing energy transformations *it is the identity of the agent transforming the energy input into end-uses* that defines what should be considered as an energy input (Cottrell, 1955). This implies that spaghetti is 'energy input' for humans but not for a refrigerator, and 1 kWh of electricity is energy input for a refrigerator but not for a starving person;

ii Primary energy versus secondary energy: In this case we focus on the distinction between energy flows made available by processes outside of human control (e.g., wind, solar energy, coal, natural gas) that cannot be produced by humans (first law of thermodynamics) and energy carriers that are produced and controlled by humans, but only by exploiting available primary energy sources;

iii Energy carriers versus end-uses: Quantities of energy carriers (electricity, fuels process heat) are simple assessments of quantities of a given form of energy that can be converted into another. On the contrary, end-uses require the specification of a profile of inputs such as the required amount and mix of energy carriers, the required number of hours of labor, the required amount of power capacity, and the requirement of space needed to convert a given profile of inputs of energy carriers into the expression of a useful task.

It is important to be aware that quantities of energy referring to different energy forms cannot be summed as such. For example, 1J of mechanical energy is different from 1J of thermal energy. This difference is at the basis of the development of the classical thermodynamics of Carnot (Giampietro et al., 2013). We observed earlier that 1 kWh generated by a wind turbine (intermittent source) has a different quality than 1 kWh generated by a gas turbine (a peaker). Quantities of primary and secondary energy sources cannot be summed together because they belong to two different descriptive domains. The availability of primary energy sources depends on natural, rather than human factors. They are produced by natural processes in the biosphere or because of boundary conditions (e.g., solar radiation). They are relevant in studying external constraints (biophysical limits). Secondary energy inputs, on the other hand, can be managed by humans (they are produced in the technosphere by technical processes), and therefore they are relevant in studying the internal constraints associated with technology.

3. The technical and practical challenges of measuring efficiency on a macroeconomic scale

Methodological issues become more complicated when the concept of efficiency is used to measure ratios of quantities defined in non-reducible descriptive domains (different dimensions of analysis) such as the energy/GDP ratio. This ratio is commonly known as the Economic Energy Intensity (EEI) indicator—one of the most commonly used aggregate measure of a nation's energy efficiency. EEI has been criticized for not measuring underlying technical efficiency because its value reflects the specific sectoral mix in the economy (Giampietro et al., 2012; Jenne and Cattell, 1983). The value of the EEI is also affected by changes in the energy input mix (Liu et al., 1992) and energy for labor substitution (Renshaw, 1981). None of these relevant factors can be dissected concisely through a simplistic measurement of efficiency.

For example, Boulding (1981) points out that in technical efficiency terms, electricity generation is a comparatively inefficient process, given the significant energy and capital required to extract and convert a quantity of primary energy sources into a smaller quantity of secondary energy. Nevertheless, despite the significant increase in overall energy consumption that coincided with the growth of the burgeoning electric power industry between 1910 and 1950 in the USA, official statistics showed a sharp reduction in the Economic Energy Intensity of the economy, as measured in real GNP per unit of energy input.

This example shows that measuring energy intensity at the national level entails losing a great deal of information, context and discriminatory power through the process of aggregation. In fact, Economic Energy Intensity is expressed in MJ/€ (megajoules of gross energy requirement per € of GDP for any given year). But then the EEI ratio can also be expressed as a ratio over two other indicators: 'energy use per capita per year' and 'GDP per capita per year'. The problem is that these two indicators are strongly correlated (Fiorito, 2013).

This means, for example, that the EEI indicator cannot distinguish between a rich country that consumes high levels of energy with high value-added production per capita per year and a poor country that consumes very little energy with very little value-added production per capita per year (Giampietro et al., 2012). The EEI ratio is an 'uncontextualized' piece of information. Fiorito (2013) demonstrated the poor discriminatory power of the EEI by showing clusters of countries that share very similar EEI values, but quite different levels of wealth and patterns of economic development (e.g., Angola, Chile, Germany, Guatemala, Norway and the Netherlands having almost the same low value of EEI, and Algeria, Australia, Lithuania, Malaysia, Thailand, Turkey, and the USA having almost the same high value of EEI).

The aggregation of data that takes place when calculating the energy intensity indicator at the national level obscures the fact that the larger the share of the service sector in the generation of the GDP, the lower the EEI of an economy (Giampietro et al., 2012). This result does not reflect changes in technical efficiency that take place at the micro-levels of an economy, but structural changes of the economy altering the original mix of sectoral GDPs.

The EEI indicator also obfuscates another key variable regarding sustainability—the extent to which energy sources are externalized to other countries, also known as the 'boundary problem'. This is a strategy adopted by developed countries (Alcántara and Roca, 1995; Proops, 1988) that is affecting the value of EEI to make it appear that countries are energy efficient when in fact they are simply displacing high levels of energy consumption to other countries. For example, a high GDP-per capita country such as Switzerland enjoys a low value of economic energy intensity because it imports the vast majority of energy inputs, food inputs and industrial products it consumes while it generates added value in the financial sector. Efficiency metrics cannot assess the level of externalization of an economy by adopting just a single numerical value. On the contrary, a detailed analysis of energy end-uses makes it possible to track the dependence on 'virtual end-uses' embodied in the imports of post-industrial economies (see section 6.2).

Finally, in the last decades another economic strategy—the increase in credit leverage and quantitative easing—has entered among the likely factors that affect the economic energy intensity of a country. Sustaining the consumption of imported goods by generating higher debt levels is an effective way of reducing the perceived biophysical/energy input required by an economy. Considering that between 2007 and 2015 credit leverage (debt) globally has increased by 57 trillion USD—more than the increase in global GDP (38 trillion USD) in the same time period—and that the vast majority of this credit has been generated and used in developed countries (McKinsey Global Institute, 2015), it becomes clear how significant this factor has been in helping post-industrial countries maintain high levels of the GDP/energy input 'efficiency' ratio.

4. The missing context in measurement—problems with applying simplistic measurements in policy

4.1. Problems with measuring efficiency over time—the Jevons Paradox

Another challenge related to efficiency measurements at the macroeconomic scale, is determined by the complexity of social-ecological adaptive systems. Complex systems adjust to changes, either generated internally or imposed on them by the context, by "becoming something else" (Prigogine, 1980). This implies that changes in efficiency eventually translate into an evolution of (change in) the definition of 'what a given activity is' and 'what the role of that activity inside the system is': this is called Jevons Paradox (Giampietro and Mayumi, 2018; Polimeni et al., 2008). A more efficient car does not just drive more miles, it becomes a different concept of car, bigger with air conditioning, 4 wheel-drive and many other gadgets.

The Jevons Paradox stipulates that when a system learns how to use a resource more efficiently, it will use the resource more, and not less because of this increase in efficiency. As predicted by Jevons (1865, p. 141):

"If the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each. And if such is not always the result within a single branch, it must be remembered that the progress of any branch of manufacture excites a new activity in most other branches".

Related to this concept is that of economics which refers to multiple 'rebound effects' (Brookes, 2000; Gillingham et al., 2016; Greening et al., 2000; Herring and Sorrell, 2009; Saunders, 2000; van den Bergh, 2011) including not only direct and indirect, but also economy-wide and systems transformational effects. However, many of the quantitative analyses of rebound, carried out within an economics frame, tend to miss the biophysical and complex nature of the phenomenon. The cause of the impossible quantification of the rebound effect is simple: a more efficient system does not do more of the same but becomes something different after the improvement in efficiency has been introduced (Giampietro and Mayumi, 2018). This implies that the data and models used to describe the system before the efficiency improvement are no longer useful to describe the system after it. This epistemological challenge has led to inconsistencies in the literature about how to conceptualize, define and measure the rebound effect [for an overview, see (Turner, 2013)]. The rebound effect challenge highlights the need for more detailed and granular accounting methods that can better show where unexpected increases in energy use and changes to the system occur.

To illustrate the pitfalls of simplistic assessments of 'efficiency' based on the calculation of an overall output/input ratio, we provide in Fig. 1 an example of energy analysis of the US food system over time. The example is based on a well-known study of Steinhart and Steinhart (1974) in the 1970s, flagging the problem of the growing dependence of US food security on fossil energy. We updated the data of the original study using a similar study done by Heller and Koeleian (2000). The paradox here is that the adoption of a simplistic definition of efficiency, based on the measurement of a given input (the commercial energy consumed by the US food system per capita per day in MJ) and a given output (food energy consumed at the household level per capita per day in MJ), would lead one to conclude that the US food system has become less efficient – from 0.15 to 0.09 in the period 1940–1995 where the US experienced a dramatic process of technological improvement. This paradox can be easily explained. When measuring efficiency (measured as an output/input ratio) by observing the characteristics of a complex system evolving in time, there are four changes making it impossible the comparison at two distant points in time. The changes refer to: 1. what is

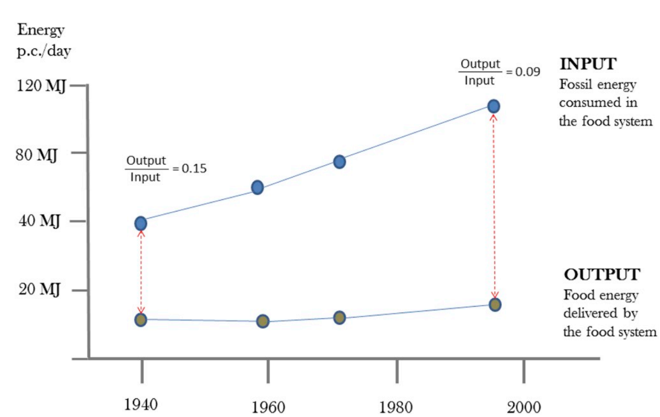


Fig. 1. Evolution of the 'efficiency' of the US food system based on fossil energy input and food energy output (in MJ per capita per day). Data 1940–1970 are from (Steinhart and Steinhart, 1974); data 1970–1995 from (Heller and Keoleian, 2000).

the output (relevant attributes to be measured); 2. what is the input (relevant attributes to be measured); 3. why the output is generated (definition of the function to be expressed with the output); 4. how the output is generated (the structural elements determining the output/input relation). Looking at the graph illustrated in Fig. 1 it is easy to identify and describe the four changes that took place in the US food system over the considered period.

1. *Change in the definition of WHAT is the output*

A dramatic increase in the share of meat in the US diet. Meat consumption went from about 40 kg per capita per year in the 1940s to almost 75 kg in the 1990s. This increase caused a rise in the primary requirement of grain to feed animals. While, this change in the quality of the diet implied a bifurcation in the assessment of the quantity of food energy (MJ/day) consumed in the diet. At household level the quantity of MJ/day consumed by the US population remained almost the same, whereas the quantity of MJ/day of food (including food used as animal feed) produced and processed by the food system skyrocketed of 6 times. It makes a big difference whether 1 MJ of dietary energy intake comes from beef or potatoes.

2. *Change in the definition of WHAT is the input*

Two changes have to be considered here: (i) In the period under analysis, the level of exports of the agricultural sector in the US increased 8 times (Dimitri et al., 2005). This means that part of the energy included in the assessment of the input to the US food system in Fig. 1 was used for food export production; (ii) the assessment of energy inputs in "joules" does not consider the implications of changes in the mix of primary energy sources (e.g. coal, oil, nuclear, alternatives sources) and the mix of energy carriers (electricity, fuels, process heat) used for the various activities undertaken in the food system (agriculture, food industry, distribution, home preparation).

3. *Change in the definition of the WHY of the output*

A dramatic increase in the convenience of food products. The preparation time of US meals in the 1940s was measured in hours, in the 1990s in minutes. This significant increase in convenience is a hallmark of modern economies. It has made more labor available for the economy as it has enabled many women to enter the paid work sector. In this case, it is the usefulness of the product or service provided (per unit of food consumed) that changed; 1 kg of food in 1940 did not have the same level of convenience as 1 kg of food in 1995. Thus, the quantification of the changes in the 'useful output' through time is missed by the assessment in Fig. 1.

4. *Change in the HOW of the process*

A dramatic change in the set of activities carried out in the food systems. Besides food production (in agriculture), other activities have been growing dramatically in terms of importance such as food processing in the food industry, packaging, transportation, final distribution, home storage and preparation. In modern food systems, the post-harvest sector uses four times more energy than the agricultural sector (Heller and Keoleian, 2000).

In conclusion, the two output/input ratios shown in Fig. 1 do not provide any useful information for studying changes in the efficiency of the US food system.

4.2. Problems in understanding the relationship between input and output levels

Measurements of efficiency often do not include sufficient information to understand the causes of changing levels of output. For example, the Energy Efficiency Directive 2012/27/EU – EED (European Parliament, 2012) had an energy efficiency target of reducing the EU's primary energy consumption by 20% by 2020. Note that this target does not measure the output (i.e., what is produced by the economy); it assumes that any reduction in primary energy consumption is a sign of increased efficiency of the economy. When the EU experienced a downward trend in the level of GHG emissions in the period 2007–2009, this reduction was attributed by the European Environment Agency (2010, p. 5) to successful efficiency policy: *"our policies and tools seem to be working"*.

However, Fig. 2 suggests that the reduction in emissions was more likely the consequence of the economic crisis that hit Europe in that period. This example shows that defining a simple percentage target for efficiency (by reducing the input) does not provide enough discriminatory power for a sound interpretation of results. The concept of efficiency must consider the complex relationship between the input and output of the system to render meaningful results.

5. Another key epistemological issue: the conceptual hurdle of input-output tables

Input-output tables are another popular tool for generating indicators of efficiency (Hatirli et al., 2005). But can input-output tables adequately identify, capture and measure the physical characteristics of the 'external referent' of the measured input/output ratio (a prerequisite for a robust and useful assessment)? Indeed, the epistemological challenge associated with the analysis of complex systems lies in the existence of *immaterial observables,* that is, relevant aspects of the system that are not material but recorded in its system of control. "A human activity system can be defined as 'notional system' (i.e. not existing in any tangible form) where human beings are undertaking some activities that achieve some purpose" (Patching, 1990).

Values reported in input-output tables generally refer to notional systems (the representation of the expected input/output relation) that map onto observable systems (the external referent that can be observed to generate the data included in the tables). However, there is a systemic degeneracy in the mapping between structural instances (characterization based on observable elements) and functional types (characterization based on notional descriptions) - for a detailed conceptual discussion, see (Giampietro et al., 2006). The problem of the systemic degeneracy in the accounting of the characteristics of structural and functional elements in input/output assessments is illustrated in Fig. 3 and Table 1.

Fig. 3 illustrates the co-existence of two different logics for the quantitative analysis of the profile of inputs and outputs describing unitary operations in the oil and gas sector: the input/output profiles for a series of *functional elements* in the oil sector (e.g., oil extraction, transport and refining) and those for the corresponding set of *structural elements*. The quantitative assessments referring to the two logics do not necessarily map onto each other. For example, oil extraction can be done with offshore and onshore plants, oil transport can be undertaken through pipelines, tankers or trucks, and oil refining can be done in small, medium and large refineries. Depending on the pre-analytical choice of the analysis, we can generate different input/output ratios for a given task. If we frame this discussion of input/output ratios in terms of 'efficiency assessments', then the efficiency of functional elements (the notional representation) is different from that of structural elements (the technical representation obtained by direct measurement of characteristics).

This point is further illustrated in Table 1. Using the technical characteristics of the structural elements –observable technical coefficients describing unitary processors – we can measure the profile of inputs per unit of output by observing the local operations of technical elements (e.g., pipelines, trucks, tankers). This is a bottom-up generation of information that can be scaled-up to a higher level of analysis if we know the relative contribution of the various structural elements to the function (shown in Table 1).

On the other hand, using aggregated statistical data, we can obtain the value of the total amount of inputs used by a given function in the system (e.g., transportation) and divide it by the value given by

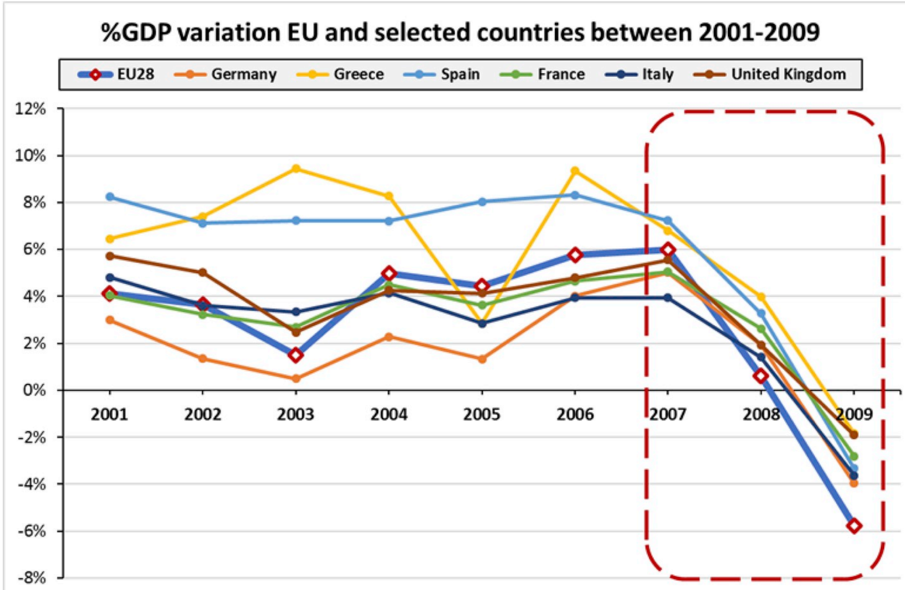


Fig. 2. Euro area GDP growth rate (at current prices): an economic explanation of the reduction of GHG emissions in the EU in the period 2007–2009. Own elaboration, data from Eurostat (2015).

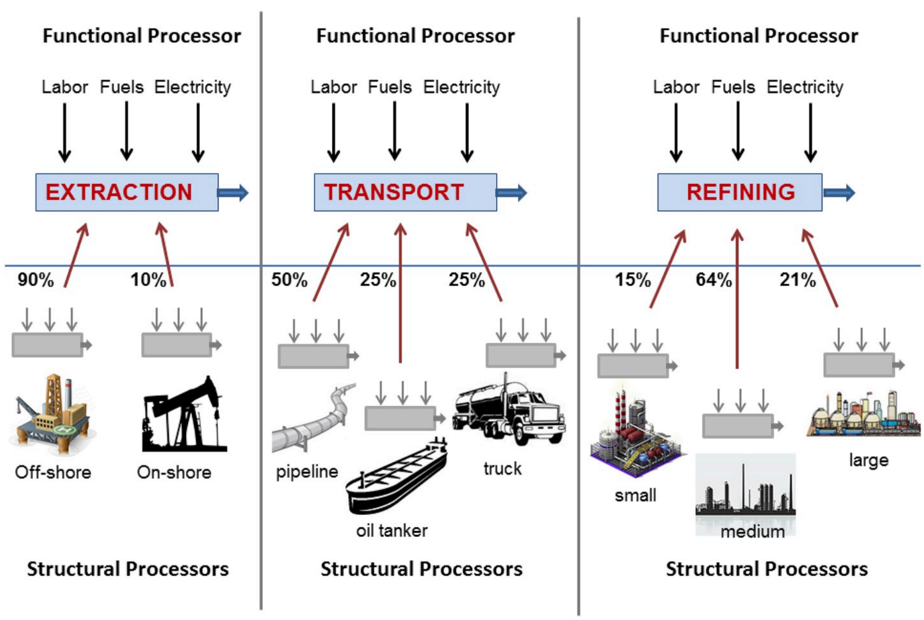


Fig. 3. The distinction between functional (notional) and structural (observable) elements in the quantitative analysis of inputs and output in the oil and gas sector (adapted from (Aragão and Giampietro, 2016).

available data on the total output. In this way, we can directly calculate the profile of inputs per unit of output for functional nodes defined for a given representation of a network of transformations. This is a top-down generation of information about a functional element (a notional representation). The problem with scaling down this information to a lower level of analysis is that it not only reflects the technical performance of the process expressing the given function, but also the highly specific combination of different local operations (the mix of structural elements) mapping onto the same function (as illustrated in Fig. 3 and Table 1).

The critical question therefore is: Do input/output tables provide the type of information required to determine the 'technical efficiency' of the structural elements determining the output/input ratio? Or instead do they provide the characteristics of a notional element reflecting the characteristics of a mix of structural elements having different technical coefficients? The degeneracy in the mapping between functional and structural suggests prudence in relation to this point.

Based on her experience in international comparisons of energy efficiency, Phylipsen et al. (1997) observed: "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". From this perspective, the only possible solution to incorporate the variance in economic structures into account (the mix of activities associated to different levels of energy intensity) is to define specific 'energy efficiency benchmarks' (Phylipsen et al., 2002) or how much energy is required to produce a given specified output.

Thus, if we want to compare industrial sectors in relation to their energy performance, it is important to carry out a pre-analytical

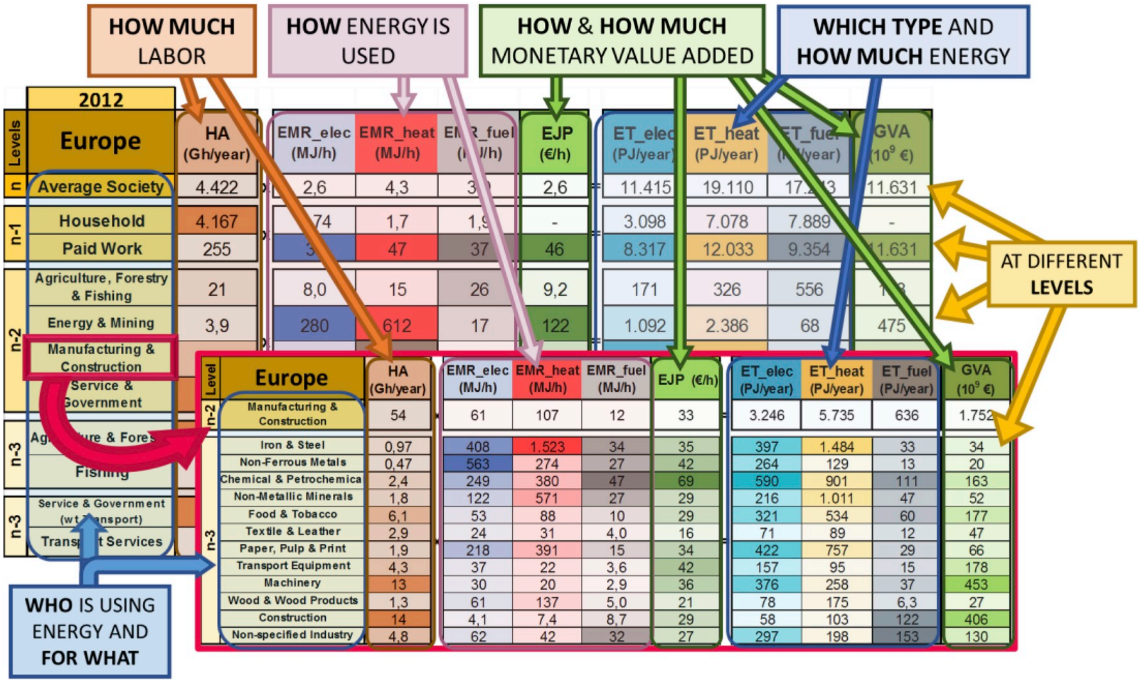


Fig. 4. The features of the information space of the energy end-use matrix. Abbreviations: HA = human activity in h (on year basis); EMR_i = energy metabolic rate of energy carrier i in MJ/h (average on year basis); EJP = economic job productivity or gross value added per hour of human activity in €/h (average on year basis); ET_i = energy throughput of energy carrier i in PJ (on year basis); GVA = gross value added in € (on year basis).

Table 1
Input/output values for a functional element (notional representation) and the corresponding set of structural elements (technical representation) according to the set of relations illustrated in Fig. 4. Data are from (Aragão and Giampietro, 2016).

	input/output ratios		
	h of work/ m^3 oil	GJ fuels/ m^3 oil	GJ electricity/ m^3 oil
Functional element			
Oil transportation (based on 50% pipelines; 25% tankers; 25% trucks)	0.71	0.24	0.005
Structural elements			
Pipelines	0.02	0.03	0.01
Tankers	0.7	0.3	n.a.
Trucks	2.1	0.6	n.a.

identification of 'equivalent classes of activities' that must share a series of common characteristics: (i) producing the same typology of products; (ii) using the same typology of inputs; (iii) adopting the same set of unitary processes for generating the output (adopt similar production technologies). For example, if we want to study the energy intensity of the paper and pulp sector in the European Union it makes no sense to compare the paper and pulp sector of Norway, which is primarily involved in cutting trees and making the paper pulp, with the one in Italy, which specializes in value-adding: buying paper and making notebooks. Even though the structural elements of the paper and pulp sectors of these two countries are grouped into the same category of accounting in available statistics (e.g., Eurostat NACE classification), they express different processes and therefore should be categorized using different labels. Velasco-Fernández et al. (2018) have elaborated this example on the basis of the energy end-use matrix.

As the example in Fig. 3 and Table 1 has shown, in order to make a meaningful comparison of the 'energy performance' of the distinctive sectors and sub-sectors of the EU economy, it would be essential to define pertinent taxonomies of (sub-)sub-sectors of industrial sectors by identifying and grouping homogeneous biophysical activities in each sector. Defining more useful taxonomies of sub-sectors is relevant for identifying specific characteristics of expected technical benchmarks. In this way, differences in the value of energy intensity across sub-sectors could be associated with differences in the biophysical characteristics of the various processes involved.

6. *The metabolic pattern of social-ecological systems and the energy end-use matrix*

The previous sections have illustrated a series of problems associated with the task of generating useful information for policy in relation to energy efficiency. It was argued that if we want to define policies aimed at improving the energy performance of a complex set of integrated processes defined at different scales (e.g., the operation of specific technologies, economic sub-sectors, economic sectors, whole economies), we need to develop a more elaborate system of accounting capable of identifying and contextualizing the various factors that are relevant for the performance of the system as a whole. Summing up uncontextualized quantities of different types of energy and material flows observed at different hierarchical levels of analysis into an 'overall input' and an 'overall output' is not likely to produce the desired result. Moreover, in relation to the accounting of energy flows of different qualities, as suggested by Leach (1975), we have also to "solve the add-up problem by avoiding it altogether: the analysis should confine itself to displaying all flows and numbers separately" (p. 341). This is the rationale behind the use of the energy end-use matrix to describe the metabolic pattern of economies.

6.1. *Conceptual description of the end-use matrix*

The field of Ecological Economics has proposed an enrichment of the conventional narratives about the economic process by broadening the set of relevant aspects in the description of the performance of an economy (Martínez-Alier and Muradian, 2015). Of particular relevance here is the concept of social-ecological systems (SES) put forward by Berkes, Folke, Holling and Gunderson among others (Berkes et al., 2003;

Berkes and Folke, 1998; Gunderson and Holling, 2002; Holling, 2001). A SES can be defined as the complex of functional and structural components operating within a prescribed boundary that is controlled in an integrated way by the activities expressed both by the given set of ecosystems (in the biosphere) and the given set of social actors and institutions operating in the economy (in the technosphere) (Giampietro, 2018). In this framing, the performance of an economy is tied to the "emergent property" determined by the interaction of lower-level functional components (e.g., economic sectors) made up of structural elements (i.e., expressing the physical processes). The emergent property is represented by the ability of the economy to reproduce and adapt according to its internal values and aspirations, while interacting with its context (Giampietro et al., 2012). The constituent components of a SES (i.e. its functional parts guaranteeing its metabolism) can be divided into: (i) the primary sectors (such as agriculture and energy and mining) that represent the catabolic part, taking advantage of favorable gradients provided by nature to supply the required inputs to the rest of society; and (ii) the 'other sectors'—representing the anabolic part, using secondary inputs supplied by the primary sectors to maintain and reproduce the society. The 'other sectors' include: manufacturing and construction, service and government and the household (residential) sector. These constituent components depend on each other in terms of essential inputs: The household sector uses inputs from all the others to reproduce and supply hours of human activity (labor) to the rest; the primary sectors use human activity, primary sources and secondary inputs to provide secondary inputs of food, energy and raw materials to the others; the manufacturing and construction sector uses human activity and secondary inputs to supply technology and infrastructures to the entire society whereas the service and government sector uses human activity and secondary inputs to reproduce institutions and maintain people.

The end-use matrix (EUM) is an accounting method that makes it possible to study the energy performance of economies and economic sectors while avoiding the practical and conceptual problems of simplifications related to the calculation of input/output ratios outlined in the previous sections (Giampietro et al., 2019; Pérez-Sánchez et al., 2019; Velasco-Fernández et al., 2019, 2018). With the end-use matrix, we can characterize the specific metabolic pattern associated with the functioning of an economy in terms of a profile of consumption of secondary energy inputs and work hours of the structural and functional components of the economy. An example of such an end-use matrix is shown in Fig. 4. It quantifies the pattern of energy end-uses in the EU across different hierarchical levels of analysis: the whole economy (at level n); the paid work sector (economic production) versus the household (residential) sector (at level n-1); the primary, secondary and tertiary sectors within the paid work sector (at level n-2); and economic sub-sectors (at level n-3).

The novel features of the approach include the following:

1. The EUM distinguishes among the different types of energy carriers used inside the economic process—electricity, liquid fuels and process heat—thus recognizing their non-comparable qualities (see Fig. 4). This distinction provides a better-informed analysis of the mix of primary energy sources required to generate the particular (or proposed) mix of energy carriers used. In fact, the end-uses described inside the energy sector—i.e. how the energy sector uses energy carriers—can be related to the various activities involved in the extraction and use of different forms of primary energy sources. That is, they map onto the required flows of primary energy sources (which are not included in the end-use matrix). If the analysis is extended to lower-level structural compartments (not shown here), the accounting framework can also distinguish between different types of fuels (e.g., diesel versus gasoline) or different types of electricity loads/supplies (e.g., baseload, peakers, or intermittent).
2. End-uses are characterized not only in terms of quantities of energy carriers used (final use), but also in terms of an expected requirement of labor. Note that 'human activity' measured in hours is equal to 'labor' when dealing with time invested in paid work.
3. End-uses are analyzed not only for the production side of the economy, but also for the consumption side (see Fig. 4). Indeed, as Zipf (1941) observed, within society energy carriers and human activity are required for *both producing and consuming* goods and services. The dynamic equilibrium between production and consumption inside the economic process entails a competition for the use of energy carriers and human activity (and other resources, such as technical capital, useful spaces, food, water, etc.). Therefore, a given metabolic pattern of society represents a special solution to the problem of how to allocate available internal resources to the various functional compartments in charge of producing and consuming goods and services and achieve a dynamic budget between production and consumption.
4. Redundancy in the end-use matrix creates mutual information in the data set—a 'sudoku effect'—useful for scenario analysis. Congruence relations between the size (e.g., the hours of labor in a year; an extensive variable) and metabolic rate and density (e.g., the electricity consumed per hour of labor averaged over a year; an intensive variable) of the various functional elements in the end-use matrix create redundancy in the information space. In fact, any given value in the matrix can be derived in two different ways (see Fig. 5):
   i. By using the expected relations over extensive variables: the sum of the quantities of a given energy carrier (e.g., MJ of fuel) consumed in the various sub-sectors of a sector must equal the total consumption of energy carrier of that sector as a whole (condition of closure). The same is true for the hours of human activity.
   ii. By using the relation between fund and flow elements: the quantity of a given flow (e.g., electricity) for any element of the matrix is equal to the product of the quantity of human activity (fund) allocated to that element and its expected metabolic rate (flow/fund ration) ($ET_i = HA_i \times EMR_i$).

The mutual information generated by the redundancy in the relations over the metabolic characteristics of functional elements across the different hierarchical levels of analysis creates a 'sudoku effect' (Giampietro and Bukkens, 2015). Sudoku refers to a popular number game in which a given set of constraints is used to identify the values of missing numbers in a 9×9 grid based on the location and value of the numbers already given. This property is useful to examine scenarios based on either downward causation (metabolic characteristics of lower-level elements have to conform to changes imposed on them by the metabolic characteristics of upper-level elements) or upward causation (metabolic characteristics of upper-level elements have to conform to changes imposed on them by the metabolic characteristics of lower-level elements). Thus, the complex information space of the end-use matrix lends itself well for carrying out contingent analyses of possible changes ('what if' questions).

5. The end-use matrix provides contextualized indicators of energy performance (see Fig. 4). How much energy of what type is used, by whom, how, and for doing what? How much human activity (labor) is required by the end-use and how much value added does it generate? Energy end-uses are contextualized within a specific economic (sub)sector (e.g., the electricity consumed in the agricultural sector is associated with the concomitant consumption of fuels and labor hours) and across different hierarchical levels of analysis (e.g., the electricity consumption of the textile subsector is characterized in relation to the electricity consumption of the entire industrial sector, which in turn is related to the characteristics of the paid work sector, etc.). In this way, the performance of an economy can be defined first in semantic terms—outside the straightjacket of conventional economic or engineering narratives (economic and technical efficiency)—by defining the relative importance for society of

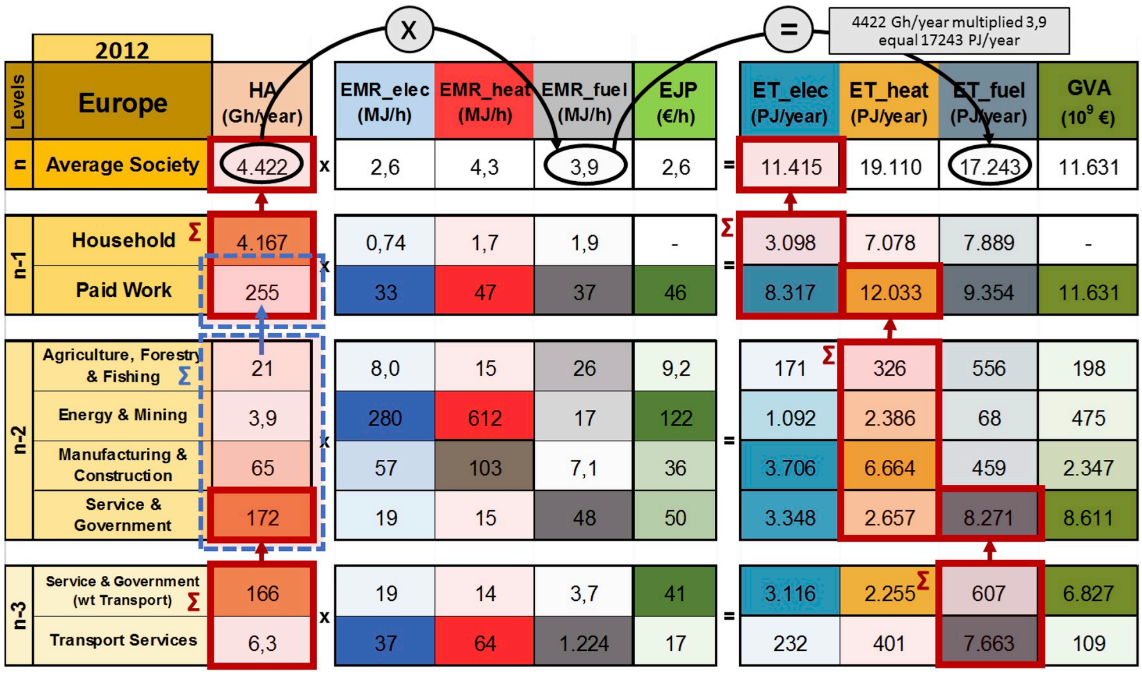


Fig. 5. Mutual information in the end-use matrix. Abbreviations: HA = human activity in h (on year basis); EMR_i = energy metabolic rate of energy carrier i in MJ/h (average on year basis); EJP = economic job productivity or gross value added per hour of human activity in €/h (average on year basis); ET_i = energy throughput of energy carrier i in PJ (on year basis); GVA = gross value added in € (on year basis).

the activities expressed by the various constituent components. This semantic definition of performance can then be formalized in quantitative terms by looking at the resulting profile of inputs (biophysical and economic costs) that the expression of these activities requires.

6. Shifts in resource use from one specific end-use to another can be tracked. This feature is particularly useful to study the Jevons paradox (or rebound effect). When the adoption of a novel technology (innovation) alters the profile of inputs of a specific end-use, it is possible to track where the spared inputs of energy carriers and human activity are reallocated inside the economy. For example, in time series we can track the movement of human activity from the agricultural sector to industry with the event of the industrial revolution, and subsequently from industry to services. In a post-industrial society, human activity and energy carriers have moved from the productive compartment (paid work) to final consumption (household). Differences in the development phase among contemporary economies (cross-sectional analysis) can easily be detected with the end-use matrix (an example is provided in Section 6.2).
7. The end-use matrix makes it possible to identify the sectors and subsectors where externalization of required resources and/or emissions to other economies takes place through the import of labor and/or energy intensive commodities.
8. The end-use matrix is transparent. It is a set of forced congruence relations over characterizations of end-uses expressed in the form of a data array. The only arbitrary decisions taken by the analyst are the definition of the categories of accounting (inputs, outputs) and the taxonomy (of economic activities) used to organize the information across different hierarchical levels of analysis. These choices are evident in the visualization of the matrix and therefore open to the scrutiny of all social actors.
9. The information space created by the EUM is based on an integration of different types of data referring to different dimensions of analysis: biophysical, economic and socio-demographic data. Therefore, the EUM is a truly transdisciplinary analytical tool.

6.2. How does the EUM solve the epistemological problems of efficiency indicators?

This section illustrates how the approach of the energy end-use matrix can resolve the pitfalls generated by the adoption of simplistic indicators of energy efficiency discussed in sections 4 and 5, namely the Jevons Paradox, illustrated by the example of the US food system (Fig. 1), the contextualization of the meaning of changes in either inputs and outputs, illustrated by the reduction in emissions in the EU during the period 2007–2010 (Fig. 2), and the limitations of notional representations of efficiency, illustrated by the analysis of the oil and gas sector (Fig. 3).

The evolution of the "efficiency" of the US food system, shown in Fig. 1, illustrates the implications of the Jevons Paradox, i.e., a comparison of two output/input ratios in time necessarily refers to two different system identities (the US food system doing different things in different ways). In Fig. 6, we summarize key changes during the period 1940–1999 that are overlooked by simplistic indicators of efficiency but that are detected by the rich information space of the energy end-use matrix. Breaking down the amount of energy used by the US society in 1940 and 1999 to provide food security by the different economic sectors, rather than providing the overall output/input ratios shown in Fig. 1 (0.15 and 0.09, respectively), other relevant changes become evident: (i) the absolute amount of energy going through the food system dramatically increased; (ii) the energy used in the household sector for food preparation dramatically increased. The additional information shown in Fig. 6 about the change in the gender ratio of the workforce of the whole US economy helps explain the reasons of the increased consumption of the food system. An increase of energy use in the food system freed up unpaid household labor during the period 1940–1999, thereby increasing the participation of women in the US formal labor force (and enabling the expansion of the US service sector).

Note that insufficient data are available to construct an end-use matrix for 1940, and Fig. 6 is therefore limited to illustrating the analytical rationale. Also, a detailed break-down of energy end-uses by food distribution and home preparation (51% altogether) is unavailable for the year 1940, so the 10% of energy consumption in the household

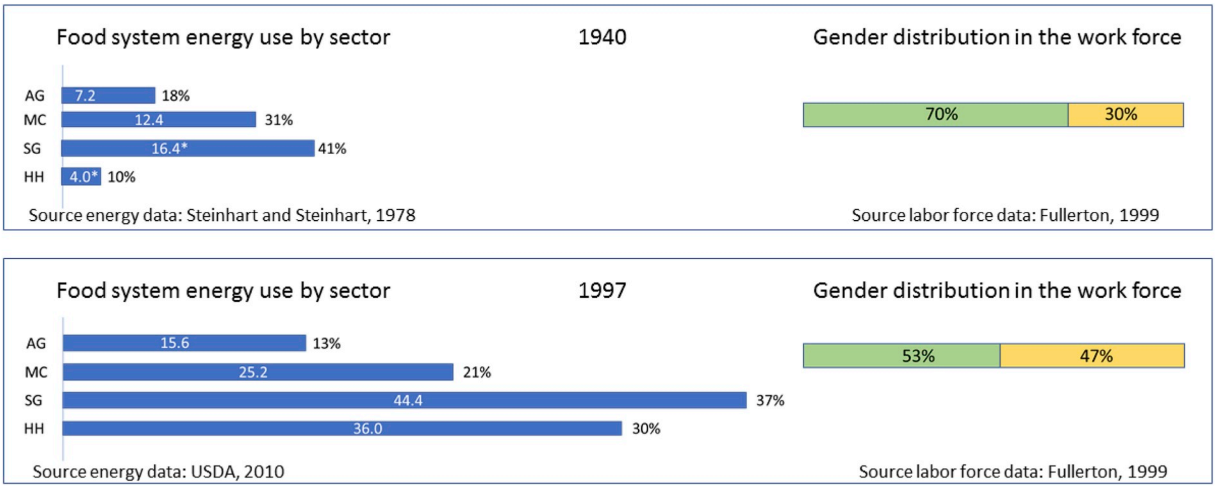


Fig. 6. Energy use (in MJ/capita/day) in the US food system by economic sector and gender ratio of the US workforce in 1940 and 1997. Abbreviations: AG = agriculture, forestry and fishery sector; MC = manufacturing and construction sector; SG = service and government sector; HH = household or residential sector. Sources: (Canning et al., 2010; Fullerton, 1999; Steinhart and Steinhart, 1974).

sector has been estimated.

As regards the reduction in emissions in the EU in the period 2007–2009 (Fig. 2), the rich information space of the EUM permits a factor decomposition analysis of energy-related emissions. As explained in Fig. 5, the energy throughput of a given economic sector (ET_i) can be written as the product of the number of working hours (HA_i) invested in that sector and its energetic metabolic rate (EMR_i; energy consumption per hour of labor). The variable HA_i reflects the size of the working time while EMR_i is a proxy of the technical capitalization of the sector (energy use per hour of labor). A sectoral decomposition analysis of the changes in the metabolic pattern of the EU over the period 2007–2015 is shown in Fig. 7. For each sector, we show the overall change in energy consumption (indicated by a green arrow) as determined by the combination of the change in HA_i (the number of working hours) and EMR_i (the energy use per hour). The household sector increased slightly in size (in terms of hours of unpaid work due to an overall increase in unemployment) but its metabolic rate was reduced, resulting in an overall slight reduction of energy use. The agricultural sector only showed minor, negligible changes. The real change (major reduction) took place in the industrial sector, which experienced not only a labor contraction (reduction in HA), but also a reduction in energy consumption per labor hour. This can be explained by closure and/or externalization (to other economies) of the most energy intensive industries/activities. Fig. 7 further indicates that the economic crisis favored a shift of working time from the industrial to the service sector. Energy consumption per hour of work was only slightly reduced in the service sector but this was more than compensated by an increase in working time. The transport sector showed a minor increase in working hours and a reduction in energy consumption per hour of work. This exercise shows that the EU policies of energy efficiency cannot explain the reduction of energy emissions during this period.

The analysis illustrated in Fig. 7 shows that at the sector level, we can identify differences in the behavior of the various sectors in relation to energy uses and emissions, but we cannot study the potential role that changes in efficiency of individual technologies may have played. To examine the effect of technological change, we have to move further

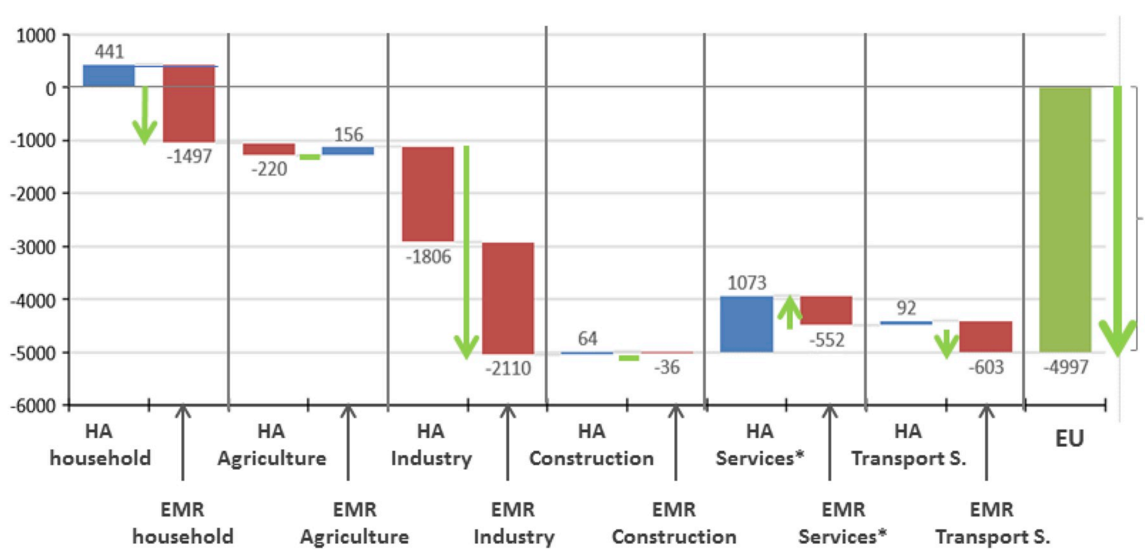


Fig. 7. Sectoral decomposition of changes in labor input (HA) and energy metabolic rate (EMR) in the EU during the period 2007–2015. Blue indicates an increase, red a reduction in sectoral value. Green arrows show the overall sectoral effect on energy consumption. The green bar on the right shows the overall reduction in energy consumption in the EU economy. Source: adapted from (Velasco-Fernández et al., 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

down in the hierarchal structure of the end-use matrix to the level of subsectors (Velasco-Fernández et al., 2019, 2018). This brings us to the third epistemological challenge discussed in Fig. 3: the distinction between notional assessments of efficiency (obtained by using top-down statistical data for "functional sectors") and technical assessments of efficiency (obtained by using bottom-up technical coefficients related to observable local processes).

In the left graph in Fig. 8, the energy metabolic intensity (EMR) of the industrial sector is plotted against its economic job productivity (added value per hour of work) for selected EU countries for the year 2012. These two factors together determine the economic energy intensity of the sector. The graph shows that the industrial sectors of Sweden, Norway and Finland have a higher energy intensity than those of the other EU countries. Can this difference be ascribed to the employment of "inefficient technologies"?

If we dig deeper into the end-use matrix, examining the differences among industrial *sub*sectors, we find that the higher energy intensity of the industrial sectors of Sweden, Norway and Finland can be explained by the relative weight of the "paper, pulp & print" subsector. The table on the right side of Fig. 8 shows that the benchmark values of the energy metabolic rate of the sub-sector "paper, pulp and print" are markedly different among the selected EU countries. Again, these differences cannot be attributed to differences in the efficiency of the technologies employed in this subsector. Sweden, Norway and Finland produce pulp and paper by the energy intensive Kraft process, whereas other countries (e.g., Hungary and Italy) import pulp and paper to produce secondary paper products. Hence the "apparent inefficiency" is generated by the choice made by statistical offices to include in the same definition of functional subsector (NACE classification) data referring to processes that do not have anything in common in terms of biophysical transformations.

6.3. *Shortcomings of the end-use matrix*

The examples provided in the previous section (section 6.2) also hint at shortcomings of the end-use matrix. First, it is evident that the approach requires the handling of a very large information space that has to be populated with data coming from different sources that not always adopt the same categorizations. Second, statistical data aggregation often implies the mixing of "apples and oranges" in the same statistical category and this makes it difficult to identify performance benchmarks that can be associated with technical efficiency. Last but certainly not least, for a comprehensive analysis of energy performance, the end-use matrix should be complemented with an analysis of the openness (level of imports) of the sectors and sub-sectors mapping material flows. This is the only way to know with certainty whether an observed reduction in energy use is simply due to the externalization of energy intensive economic activities or to a decrease in the value of benchmarks describing the characteristics of biophysical processes.

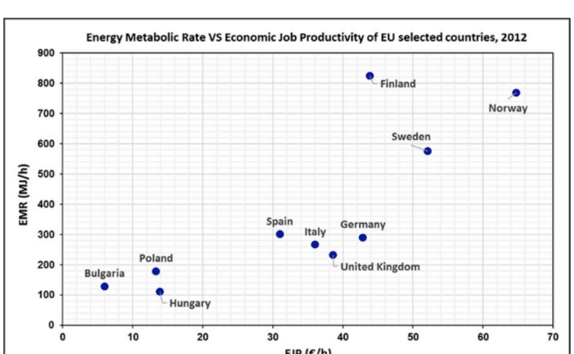
7. Conclusion and policy implications

To properly inform energy policy we need more effective analyses of the performance of socio-economic activities in relation to energy uses. EU economies are not meeting their energy efficiency targets (Eurostat, 2018) while global greenhouse gas emissions are rising overall (IEA, 2018). One of the possible explanations for these policy failures is that expected energy savings from efficiency improvements have fallen short due to the rebound effect. However, the current understanding of the rebound effect is highly variable, confused and contradictory (Turner, 2013). This is due to the mismatch in scale between the representations of the improvement in the efficiency of local processes and the consequent re-adjustments of activities in the metabolic pattern (Jevons' Paradox). Better methodologies are required to fill the knowledge gap and understand and anticipate undesirable effects (Madlener and Turner, 2016). The concept of the metabolic pattern of a SES identifies the activities of a set of expected functions needed to reproduce the structural elements of society. The metabolic pattern can be represented as a combination of end-uses of energy carriers per unit of human activity (i.e. metabolic rates). The set of expected functions must guarantee: (i) a desirable quality of life (compatible with aspirations, values) to stabilize the social fabric; (ii) a viable set of integrated processes in the technosphere (compatible with technical, institutional and economic constraints) providing stability and adaptability; and (iii) a feasible profile of flows exchanged with the context (trade with other SES and the gathering and dumping of flows from/in the local biosphere), thereby preventing the loss of favorable boundary conditions providing stability and adaptability.

The simplifications associated with the current use of the concept of energy efficiency are not helping the development of a holistic perception of the performance of social-ecological systems. Framing energy targets in terms of energy savings (absolute reductions of use) or weak indicators such as Economic Energy Intensity do not solve the problem. Simple output/input indicators especially fail to capture complex structural and functional processes, such as the Jevons Paradox/rebound effect and externalization, when measuring energy flows across different scales and levels of organization. Other methods have been developed that analyze the economy-wide energy performance distinguishing between different production processes and addressing the issue of capital-labor substitution (Zhou et al., 2012). However, while useful at the level of production processes, they remain within the conventional narrative of economics.

The metabolic narrative underlying the end-use matrix defines the socio-economic system as a complex adaptive system observed across different hierarchical levels and dimensions of analysis. The resulting accounting of its energy performance is extremely transparent and this improves the usefulness of the quantitative analysis for energy policy and governance processes (Turmes and Rivasi, 2017).

Finally, the end-use matrix is a semantically open tool. The specific



Paper, Pulp and Print	EMR_elec (MJ/h)	EMR_heat (MJ/h)	EMR_fuel (MJ/h)	EJP (€/h)	EMR_GER (MJ/h)
Bulgaria	44	256	6.8	6.3	377
Finland	1,386	3,095	61	67	6746
Germany	192	285	5.0	39	787
Hungary	47	71	2.8	13	196
Italy	142	123	8.8	36	498
Norway	968	527	101	56	3135
Poland	91	245	11	18	492
Spain	107	313	26	32	616
Sweden	1,069	2,023	98	57	4889
United Kingdom	129	88	3.7	35	426

Fig. 8. Energy metabolic rate (EMR in MJ/h) and economic job (or labor) productivity (EJP in EUR/h) of the industrial sector (left-hand graph) and paper, pulp and print subsector (right-hand table) in selected EU countries in the year 2012. Data from (Velasco-Fernández, 2017).

metabolic characteristics in the accounting categories, as well as the hierarchical levels of analysis, can be selected by the user according to the purpose of the analysis. Current research is focused on expanding the end-use matrix to include other flow inputs (material products, water, food) and fund inputs (power capacity, land use) in order to move the analysis from energy to a systems-wide material-water-energy-food nexus analysis.

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.

Acknowledgment

We are indebted to Sandra G.F. Bukkens for editing the text and her useful comments and suggestions. We also wish to thank the anonymous reviewers for their helpful input. The authors gratefully acknowledge funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No. 649342 (EUFORIE) (MG and RVF) and No. 689669 (MAGIC) (MG, RVF and TD). RVF also acknowledges funding received from the Ministerio de Educación, Cultura y Deporte (MECD) of Spain (FPU12/05711). The Institute of Environmental Science and Technology (ICTA) has received financial support from the Spanish Ministry of Science, Innovation and Universities through the "María de Maeztu" program for Units of Excellence (MDM-2015-0552). This work reflects only the authors' view; the funding agencies are not responsible for any use that may be made of the information it contains.

References

Alcántara, V., Roca, J., 1995. Energy and CO2 emissions in Spain. Energy Econ. 17, 221–230. https://doi.org/10.1016/0140-9883(95)00014-L.

Alexander, J.K., 2008. The mantra of Efficiency. In: From Waterwheel to Social Control. The Johns Hopkins University Press, Baltimore.

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

Ayres, R.U., Warr, B., 2005. Accounting for growth: the role of physical work. Struct. Chang. Econ. Dyn. 16, 181–209. https://doi.org/10.1016/j.strueco.2003.10.003.

Berkes, F., Colding, J., Folke, C., 2003. Navigating Social-Ecological Systems : Building Resilience for Complexity and Change. Cambridge University Press, New York .

Berkes, F., Folke, C., 1998. Linking social and ecological systems for resilience and sustainability. In: Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience, pp. 1–25.

Boulding, K.E., 1981. Evolutionary Economics. Sage Publications, Beverley Hills, California.

Brookes, L., 2000. Energy efficiency fallacies revisited. Energy Policy 28, 355–366. https://doi.org/10.1016/S0301-4215(00)00030-6.

Bullard, C.W., Herendeen, R.A., 1975. The energy cost of goods and services. Energy Policy 3, 268–278. https://doi.org/10.1016/0301-4215(75)90035-X.

Bundesrechnungshof, 2016. Advisory report to the budget commitee of the German parliament. Pursuant to article 88 (2) federal budget code - key issue: chapter 0903, energy and climate fund. In: Ref. :VIII 4 - 2016 - 0722. Bonn, den 21. Dezember 2016.

Canning, P., Charles, A., Huang, S., Polenske, K.R., Waters, A., 2010. Energy Use in the U. S. Food System. Economic Research Report No. 94.

Carnot, S., 1897. Reflections on the Motive Power of Fire, and on Machines Fitted to Develop that Power. John Wiley & Sons, New York.

Chapman, P.F., 1974. Energy costs: a review of methods. Energy Policy 2, 91–103.

Cottrell, F., 1955. Energy and Society: the Relation between Energy, Social Changes, and Economic Development. McGraw-Hill.

Dimitri, C., Effland, A., Conklin, N., 2005. The 20th Century Transformation of U . S . Agriculture and Farm Policy the 20th Century and Farm Policy.

European Comission, 2016. Clean energy for all europeans. Commun. from Comm. Eur. Parliam. Counc. Eur. Econ. Soc. Comm. Comm. Reg. Eur. Invest. Bank.

European Commission, 2016. Proposal for a Directive of the European Parliament and of the Council Amending Directive 2012/27. EU on Energy Efficiency, Brussels.

European Environment Agency, 2010. EU Greenhouse Gas Emissions: More than Half Way to the '20 % Target by 2020''' 3.

European Parliament, 2012. Directive 2012/27/EU of the european parliament and of the council of 25 october 2012 on energy efficiency. Off. J. Eur. Union Dir. https://doi.org/10.3000/19770677.L_2012.315.eng.

Eurostat, 2018. Consumption in the EU above the Energy Efficiency Target ([WWW Document]).

Eurostat, 2015. National Accounts by 10 branches - aggregates at current prices [WWW Document]. URL. http://ec.europa.eu/eurostat/web/products-datasets/-/nama_nace10_c. accessed 11.10.15).

Fell, M.J., 2017. Energy services: a conceptual review. Energy Res. Soc. Sci. 27, 129–140. https://doi.org/10.1016/j.erss.2017.02.010.

Fiorito, G., 2013. Can we use the energy intensity indicator to study "decoupling" in modern economies? J. Clean. Prod. 47, 465–473. https://doi.org/10.1016/j.jclepro.2012.12.031.

Fullerton, H.N.J., 1999. Labor force participation: 75 years of change, 1950–98 and 1998–2025. Mon. Labour Rev. 122, 3–12.

Funtowicz, S., Ravetz, J., 1990. Uncertainty and Quality in Science for Policy.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process, 1971st ed. Hardvard University Press, Cambridge, Massachusetts, MA.

Giampietro, M., 2018. Anticipation in agriculture. In: Handbook of Anticipation. Springer International Publishing, Cham, pp. 1–35.

Giampietro, M., Allen, T.F.H.H., Mayumi, K., Farrell, K.N., Winkler, R., Giampietro, M., Allen, T.F.H.H., Mayumi, K., 2006. The epistemological predicament associated with purposive quantitative analysis. Ecol. Complex. 3, 307–327. https://doi.org/10.1016/j.ecocom.2007.02.005.

Giampietro, M., Bukkens, S.G.F., 2015. Analogy between Sudoku and the multi-scale integrated analysis of societal metabolism. Ecol. Inf. 26, 18–28. https://doi.org/10.1016/j.ecoinf.2014.07.007.

Giampietro, M., Mayumi, K., 2018. Unraveling the complexity of the Jevons paradox: the link between innovation, efficiency, and sustainability. Front. Energy Res. 6, 1–13. https://doi.org/10.3389/fenrg.2018.00026.

Giampietro, M., Mayumi, K., 2008. The Jevons paradox: the evolution of complex adaptive systems and the challenge for scientific analysis. In: Polimeni, J.M., Mayumi, K., Giampietro, M., Alcott, B. (Eds.), The Jevons Paradox and the Myth of Resource Efficiency Improvements. Earthscan Research Edition, London, p. 200.

Giampietro, M., Mayumi, K., Sorman, A., 2012. The Metabolic Pattern of Societies: where Economists Fall Short. Routledge, New York.

Giampietro, M., Pimentel, D., 1992. Energy efficiency and nutrition in societies base on human labour. Ecol. Food Nutr. 28, 11–32.

Giampietro, M., Pimentel, D., 1991. Energy efficiency: assessing the interaction between humans and their environment. Ecol. Econ. 4, 117–144. https://doi.org/10.1016/0921-8009(91)90025-A.

Giampietro, M., Sorman, A.H., 2012. Are energy statistics useful for making energy scenarios? Energy 37, 5–17. https://doi.org/10.1016/j.energy.2011.08.038.

Giampietro, M., Sorman, A.H., Mayumi, K., 2013. Energy Analysis for a Sustainable Future : Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge, Hoboken , 2013, London.

Giampietro, M., Velasco-Fernández, R., Ripa, M., 2019. Characterizing the factors determining "energy efficiency" of an economy using the multi-level end use matrix of energy carriers. EUFORIE Deliverable 4 (2) version 3.0.

Gillingham, K., Rapson, D., Wagner, G., 2016. The Rebound Eff. Energy Effic. Policy 10, 68–88. https://doi.org/10.1093/reep/rev017.

Greening, L.A., Greene, D.L., Di, C., 2000. Energy Eff. Consum. Rebound Eff. Surv. 28, 389–401.

Gunderson, L.H., Holling, C.S. (Eds.), 2002. Panarchy : Understanding Transformations in Human and Natural Systems. Island Press, Washington, D.C ([etc.] :).

Hatirli, S.A., Ozkan, B., Fert, C., 2005. An econometric analysis of energy input-output in Turkish agriculture. Renew. Sustain. Energy Rev. 9, 608–623. https://doi.org/10.1016/j.rser.2004.07.001.

Heller, M.C., Keoleian, G., 2000. Life cycle-based sustainability indicators for assessment of the U.S. food system. Rep. Cent. Sustain. Syst. Sch. Nat. Resour. Environ. Univ. Michigan 59.

Herendeen, R.A., 1981. Energy intensities in ecological and economic systems. J. Theor. Biol. 91, 607–620. https://doi.org/10.1016/0022-5193(81)90213-7.

Herring, H., Sorrell, S., 2009. Energy Efficiency and Sustainable Consumption: the Rebound Effect. Palgrave Macmillan, London.

Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405. https://doi.org/10.1007/s10021-001-0101-5.

IEA, 2018. Global Energy & CO2 Status Report.

IFIAS (International Federation of Institutes for Advanced Study), 1974. Energy analysis. Workshop on methodology and conventions. Report No.6. In: Workshop Report. IFIAS, Stockhom, p. 89.

Inhaber, H., 1997. Why Energy Conservation Fails. Greenwood Publishing Group.

Jenne, C.a., Cattell, R.K., 1983. Structural change and energy efficiency in industry. Energy Econ. 5, 114–123. https://doi.org/10.1016/0140-9883(83)90018-X.

Jevons, W.S., 1865. The Coal Question: an Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of the Coal-Mines. Macmillan Publishers.

Labanca, N., Bertoldi, P., 2018. Beyond energy efficiency and individual behaviours: policy insights from social practice theories. Energy Policy 115, 494–502. https://doi.org/10.1016/j.enpol.2018.01.027.

Leach, G., 1975. Net energy analysis - is it any use? Energy Policy 3, 332–344. https://doi.org/10.1016/0301-4215(75)90041-5.

Liu, X.Q., Ang, B.W., Ong, H.L., 1992. Interfuel substitution and decomposition of changes in industrial energy consumption. Energy 17, 689–696. https://doi.org/10.1016/0360-5442(92)90076-C.

Lotka, A.J., 1925. Elements of physical biology, 435. Williams Wilkins Co.

Lutzenhiser, L., 2014. Through the energy efficiency looking glass. Energy Res. Soc. Sci. 1, 141–151. https://doi.org/10.1016/j.erss.2014.03.011.

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

Madlener, R., Turner, K., 2016. After 35 years of rebound research in economics: where do we stand? In: Santarius, T., Walnum, H.J., Aall, C. (Eds.), Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon. Springer, pp. 17–37.

Martínez-Alier, J., Muradian, R. (Eds.), 2015. Handbook of Ecological Economics. Edward Elgar Publishers.

McKinsey Global Institute, 2015. Debt and (Not Much) Deleveraging.

Patching, D., 1990. Practical Soft Systems Analysis. Pitman.

Patterson, M.G., 1996. What is energy efficiency? Concepts, indicators and methodological issues. Energy Policy 24, 377–390. https://doi.org/10.1016/0301-4215(96)00017-1.

Phylipsen, D., Blok, K., Worrell, E., Beer, J. De, 2002. Benchmarking the energy efficiency of Dutch industry : an assessment of the expected effect on energy consumption and CO 2 emissions. Energy Policy 30, 663–679.

Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., Ripa, M., 2019. Characterizing the metabolic pattern of urban systems using MuSIASEM: The case of Barcelona. Energy Policy 124, 13–22. https://doi.org/10.1016/j.enpol.2018.09.028.

Phylipsen, G.J.M., Blok, K., Worrell, E., 1997. International comparisons of energy efficiency-Methodologies for the manufacturing industry. Energy Policy 25, 715–725. https://doi.org/10.1016/S0301-4215(97)00063-3.

Polimeni, J.M., Mayumi, K., Giampietro, M., Alcott, B., 2008. The Jevons Paradox and the Myth of Resource Efficiency Improvements. Earthscan, London.

Price, E.H.M., 1995. Energy efficiency - a role for government or best left to consenting adults? In: MacKerron, G., Pearson, P. (Eds.), UK Energy Experience. Imperial College Press, London, pp. 309–325.

Prigogine, I., 1980. From Being to Becoming. San Fr.

Proops, J.L.R., 1988. In: Ciaschini, M. (Ed.), Energy Intensities, Input-Output Analysis and Economic Development, pp. 201–215, 1988.

Renner, A., Giampietro, M., 2020. Socio-technical discourses of European electricity decarbonization: contesting narrative credibility and legitimacy with quantitative story-telling. Energy Res. Soc. Sci. 59, 101279. https://doi.org/10.1016/j.erss.2019.101279.

Renshaw, E.F., 1981. Energy efficiency and the slump in labour productivity in the USA. Energy Econ. 3, 36–42. https://doi.org/10.1016/0140-9883(81)90005-0.

Rodgers, D.T., 1998. Atlantic Crossings. Social Politics in a Progressive Age. Harvard University Press.

Saunders, H.D., 2000. A view from the macro side: rebound, backfire, and Khazzoom-Brookes. Energy Policy 28, 439–449. https://doi.org/10.1016/S0301-4215(00)00024-0.

Scholz, R., Beckmann, M., Pieper, C., Muster, M., Weber, R., 2014. Considerations on providing the energy needs using exclusively renewable sources: Energiewende in Germany. Renew. Sustain. Energy Rev. 35, 109–125. https://doi.org/10.1016/j.rser.2014.03.053.

Shove, E., 2017. What is wrong with energy efficiency? Build. Res. Inf. 0, 1–11. https://doi.org/10.1080/09613218.2017.1361746.

Steinhart, J.S., Steinhart, C.E., 1974. Energy use in the U.S. Food system. Science 184, 307–316 (80-.).

Turmes, C., Rivasi, M., 2017. Proposal for a Regulation COM(2016)0759 - C8-0497/2016 – 2016/0375(COD). Governance of the Energy Union, Brussels, Belgium.

Turner, K., 2013. "Rebound" effects from increased energy efficiency: a time to pause and reflect. Energy J. 34, 25–43.

van den Bergh, J.C.J.M., 2011. Energy conservation more effective with rebound policy. Environ. Resour. Econ. 48, 43–58. https://doi.org/10.1007/s10640-010-9396-z.

Velasco-Fernández, R., 2017. The pattern of socio-ecological systems. In: A Focus on Energy, Human Activity, Value Added and Material Products. Universitat Autònoma de Barcelona.

Velasco-Fernández, R., Chen, L., Pérez-Sánchez, L., Giampietro, M., 2019. Multi-scale integrated comparison of the metabolic pattern of EU28 and China in time. EUFORIE Deliverable 4 (4) version 2.0.

Velasco-Fernández, R., Giampietro, M., Bukkens, S.G.F., 2018. Analyzing the energy performance of manufacturing across levels using the end-use matrix. Energy 161, 559–572.

Zhou, P., Ang, B.W., Zhou, D.Q., 2012. Measuring economy-wide energy efficiency performance: a parametric frontier approach. Appl. Energy 90, 196–200. https://doi.org/10.1016/j.apenergy.2011.02.025.

Zipf, G.K., 1941. National unity and disunity, the nation as a bio-social organism. Sociometry 4, 418. https://doi.org/10.2307/2785145.