Characterizing Energy Efficiency from the Matrix of Production of Energy Carriers at the National Level

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HISTORY OF CHANGES		
Version	**Publication date**	**Change**
1.0	March 2017	Initial version
2.0	November 2017	Revision in response to Project Review (Reporting Period 1): - A new section (F*indings and policy recommendation)* has been introduced in the executive summary in which a positive framing of the findings has been provided (the deliverable proposes a solution to existing problems). - New examples have been introduced in the text (e.g. the new Fig. 1) in order to better illustrate the relevance of the analysis given in the deliverable in relation to energy policies. - A new figure (Figure 1 Factors affecting the energy and carbon intensity of an economy) has been introduced with a short text providing substantiation of the statements about EED. Examples have been described in relation to the similar problem faced with NEEAPs. - The text has been reviewed in order to better clarify why the examples (e.g. Amish) are pertinent for the discussion and explain the use of technical terms. - The use of the analogy with the biological function of the heart has been better explained (pag. 84 and 85) as an intuitive example of network niche (explaining the same concept using network theory probably would be much more difficult to explain). - The concept of hypercycle has been better explained also in plain terms (on pag. 63) - A new "wrap up" section has been introduced at the end discussing (i) the possibilities and limits of the new approach; (ii) the test and validation of the approach carried out in section 2; and (iii) the advantages of the proposed approach compared with the business as usual approach.
3.0	April, 2019	Revision in response to project review: - An executive summary section has been introduced. - Boxes explaining MuSIASEM, Sudoku effect and End use Matrix have been introduced . - - Correction of typos.

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Executive Summary

I.The issue to be explored

The concept of energy efficiency plays a key role in structuring the discussion and shaping the quantitative analysis used to inform energy policy. However, existing policies for reducing energy consumption and emissions, based on energy efficiency targets, are not effective in achieving the expected results. This failure can be explained by considering that while the term "efficiency" appears to be straightforward – the idea is to use less input for the greatest amount of useful output - on a practical and conceptual level efficiency is an ambiguous and problematic concept to implement in order to save energy and reduce greenhouse gas emissions. This is problematic because the way energy efficiency is measured depends on pre-analytical choices of: (i) "what" it is measured as "energy"; (ii) "how" to characterize in quantitative terms "energy uses"; and (iii) "why" the quantitative assessment is relevant (the purpose of the analysis). These pre-analytical choices entail scientific and political value judgements and entail the co-existence of different definitions of "efficiency". Relying on individual "efficiency" measurements means assuming that we can identify the best course of actions by measuring a simple number – an output/input ratio calculated using just one of the possible definitions of "energy" at a given scale and in relation to just a given definition of relevance. This assumption has a detrimental effect on the quality of the choice of energy policies. In fact, it not only implies hypocognition (the missing of relevant aspects of the issue to be studied) but it also allows that the most powerful actors can cherry pick the specific output/input ratio - one of the possible indicators of energy efficiency - that best matches their agenda. 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 (e.g. Economic Energy Intensity).

In this deliverable we carry out a quality check on the usefulness of the concept of energy efficiency when applied to the study of the performance of technical processes and when used to generate indicators and targets used in policies related to sustainability.

II. What was done to investigate it

We used two approaches:

(i) a conceptual analysis based on a critical appraisal of indicators based on the know-how available in theoretical foundations of energetics – the disciplines that studies how to account energy transformations in self-organizing systems.

(ii) an empirical analysis confirming the validity of the concerns expressed in the critical appraisal. Actual assessments are used to illustrate examples of key aspects missed by the actual protocols of assessment of energy efficiency. These protocols entail comparing "apples" and "oranges".

III. The method employed

In the section identifying the conceptual flaws making useless (and dangerous) the existing approach to energy efficiency we provide a crash course of energetics – i.e. how to properly account quantities of different types of energy forms interacting in a network of transformations.

1. Not all the joules are the same: what are the categories of accounting that should be used in energetics; how to handle differences in quality (1 J of electricity is different from 1 J of gasoline, and 1 kWh of peak electricity is more valuable than 1 kWh of intermittent electricity, etc.);

2. Flagging the fact that statistical offices are not providing a sound assessment of energy quantities - the assessments of the quantity of the "same flow of energy" in a given country are different when considering different statistical sources!

3. The deep epistemological challenge of assessing in quantitative terms the characteristics of "becoming systems" – the Jevons paradox – implies that a more efficient system will change, in the long term, its identity and behavior (it adapts to the improvement). It is impossible to predict the future consequences of increases in efficiency using deterministic/econometric models

As an alternative, we propose another approach to energy accounting – the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism – that can be used to assess the "performance" (not efficiency) of complex adaptive systems (such as societies). The MuSIASEM approach (that is applied in the other deliverables of this Work Package) is illustrated in relation to the possibility of carrying out an analysis across levels of analysis – i.e. the whole economy, individual economic sectors, sub-sector of sectors.

IV. The data and sources

The collection of information regarding Fund and Flow elements used in the energy sector has been obtained organizing data on non-equivalent acounting categories: (i) Primary Energy Sources (whether domestically produced or imported) and (ii) Energy Carriers divided in electricity, derived heat or fuels (whether domestically produced or imported). Data have been obtained from the following data sources:

1. *International Energy Agency* (http://www.iea.org/sankey/) organized in Sankey flow diagrams;
2. *Eurostat database* for specific data such as electricity, gas, petroleum products used in CHP and Heat Plants, Petroleum Refineries, Coke Ovens, Oil and Gas Extraction, Coal Mines and Nuclear Industry, the energy balances - [nrg_100a] (http://ec.europa.eu/eurostat/data/database);
3. *European Environmental Agency Greenhouse Gas Emissions* [env_air_gge] database for data on emissions for energy provision processes (Public Electricity & Heat Prod, Petroleum Refining and Manufacture of Solid Fuels and Other Energy Industries) (http://www.eea.europa.eu/data-and-maps/);
4. *Enipedia database* (http://enipedia.tudelft.nl) for data about Power Capacities and Power Generation Technology (fund elements) by country by fuel type. (more about enipedia in C.B.Davis, A. Chmieliauskas, G.P.J. Dijkema, I. Nikolic (2015), Enipedia, enipedia.tudelft.nl, Energy & Industry group, Faculty of Technology, Policy and Management, TU Delft, Delft, The Netherlands).

V. The results

In the section identifying the conceptual flaws of the implementation of the concept of efficiency, we provide a series of practical examples showing that the concept of “efficiency” is simplistic and therefore it cannot be used to develop indicators and policy targets and indicators: (i) confusing reduction of consumption (e.g. because of an economic crisis) with an improvement of efficiency; (ii) the fatal attractor of mixing economic analysis with energetic analysis – the blunder of the economic energy efficiency indicator (EEI). We show that at the level of whole countries the EEI index is totally useless for comparing the energy performance of countries or studying the factors determining their EEI; (iii) in order to individuating factors explaining differences in the energy intensity of the economy one has to move to a lower level of analysis (at the level of economic sectors). Difference in the structure of the economy – the relative importance of the service and the industrial sector in the GDP – do affect the energy intensity independently of the efficiency of the technologies used in the economy; (iv) the openness of the economy and the massive reliance on credit leverage affect the overall assessment. Countries printing money and importing all the industrial products they consume will result less energy intensive than other countries. This has nothing to do with the efficiency of their technologies.

In the section presenting an empirical analysis we show the very high level of openness (dependence on imports) of the EU28 countries in relation to: (i) imports of Primary Energy Sources (fossil energy and uranium minerals); (ii) imports of energy carriers (liquid fuels and electricity). Using the MuSIASEM approach we assess the effect of “externalization” (a sort of technological foot-print) of the production of these flows for the various EU countries. Finally, we also address the issue of power capacity – the technical infrastructures needed to generate and make available energy carriers to the economy. This final section has the goal of illustrating the importance of looking not only at energy flows or stocks (how to change primary energy sources into of joules of energy carriers, or energy carriers into energy end-uses) but also to the required structural and functional elements making possible these transformations (e.g. power capacity and infrastructure in the energy sector). The analysis of this issue is done in general in economic terms – i.e. analyzing the required investments for changing the energy matrix, - but never in biophysical terms as we do.

VI. Significance of the results for policy-makers (usefulness for governance)

The discussion of energy policies based on single and uncontextualized efficiency indicators should be avoided due to the bias introduced by the pre-analytical definition of the definition of “efficiency” (reflecting the priority given to a specific concern). Instead, the discussion should be framed by considering a plurality of concerns to be addressed and translated into a set of non-equivalent definitions of “efficiency” referring to different criteria – moving to the concept of multi-level energy performance (multi-criteria and multi-scale analysis). In relation to this point, the adoption of the rationale of the metabolic pattern can dramatically help the tracking of flows of energy carriers looking at the two interfaces: (i) production of energy carriers - what type of funds (e.g. power plants, distribution infrastructure) are required in the energy sector to produce the different types of energy carriers – depending of the given mix of primary energy sources; and (ii) consumption of energy carriers - what type of funds (e.g. cars, trains) are required in the other compartments of the society to use energy carriers to do what. The rationale of metabolic patterning allows one to identify which energy carriers are used by specific societal compartments and then to associate them with specific societal functions.

VII. Their significance for stakeholders

A transition to a low carbon economy can only be achieved if the society is capable of changing in a coordinate way the pattern of production and the pattern of use of energy carriers. If we keep looking and studying the problem of energy supply in isolation - considering it as a technical problem to be solved by engineers and technology – we will never find any effective solution. Generating new technological gadgets will not solve our problems of sustainability. Moreover, technological innovation allowing relative energy savings may lead to increases in energy consumption (Jevons paradox). We have to learn how to express a new set of social practices. Consequently, the rest of society has to be involved in the co-production of knowledge about how to move to feasible, viable and desirable metabolic pattern.

VIII. Their significance for other researchers (plausibility of scientific inquiry)

The challenge of energetics is the challenge of complexity. Energetics cannot be handled using reductionism (simplistic analysis). Complex energy metrics require the adoption of the rationale of metabolic analysis – i.e. applying relational analysis to energy transformations across levels and scales. There are several non-equivalent ways of accounting energy flows, all of which are needed to assess the performance of an economy. Three essential categories are: (1) primary energy sources (e.g., coal, wind, hydro, oil); (2) energy carriers (e.g., electricity, fuels, process heat); and (3) energy end-uses (quantitative characterization of what is achieved by the use of energy in relation to known social practices). Often these distinctions are not (properly) used in the development of policy targets and policy evaluations. Unfortunately, without a proper pre-analytical identification of the distinctions to be made in relation to the purpose of the analysis, it becomes problematic to have an effective analysis of the changes that a policy can generate when considering different criteria of performance. As shown by the failure of the Energiewende in Germany – where regulation and incentives to intermittent energy forms without a proper demand adaptation have prompt the use of coal power plants as peakers for stabilizing the net, increasing electricity prices and CO2 emissions - not even kWh of electricity are the same!

The rationale of metabolic analysis makes it possible to associate a flow of energy (e.g. a given amount of food or a given amount of gasoline) to a given fund element (e.g. a person or a car) used to fulfill a goal (e.g. surviving or driving to a given destination). This makes the representation of a quantity of energy (a flow) much richer by contextualizing its assessment in relation to two converters: (i) the fund that has generated the flow; (ii) the fund that uses the flows; and (iii) a task – why the flow is processed by the fund. For example, if you have a given quantity of food energy you must have a fund that produced it (e.g. farmers using hectares of cropland) and a fund that is consuming it (e.g. dietary intake of people). The same applies to electricity, we need a fund that produced it (e.g. a nuclear power plant) and a fund that uses it (e.g. the appliances in the residential sector). Assessing the network of energy transformations using a combination of flow-fund relations – associated with a network of flows and a set of funds - provides a much more robust understanding of the problems than just discussing in terms of generic energy flows.

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Abbreviations

AF – Agriculture, forestry and fishing

AFO - Agriculture and Forestry

AS – Average Society

Co - Construction

CP - Chemicals and Petrochemicals

EC - Energy Carriers

EEI - Economic Energy Intensity

EJP – Economic Job Productivity

Elec – Electricity

EM – Energy and Mining sector

ES – Energy Sector

EU – End Use

FI - Fishing

FT - Food and Tobacco

GVA – Gross Value Added

HA – Human Activity

HH – Household Sector

IS - Iron and Steel

Ma - Machinery

MC – Manufacturing and Construction sector

MQ - Mining and Quarrying for non-energy use

MuSIASEM - Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

NF - Non-ferrous Metals

NM – Non-metallic Minerals

NS - Non-Specified Industry

PES - Primary Energy Sources

PPP - Pulp, Paper and Print

SG_nTS - Services and Government without Transport Sector

TL – Textiles and leather

TET – Total Energy Throughput

TE - Transport Equipment

TS - Transport Sector

WWP - Wood and Wood Products

EU-27 Member States include: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and the United Kingdom.

EU-22 Member States include: the member countries of the European Union, with the exception of Cyprus, Denmark, Estonia, France, Luxembourg, Malta

Units and key concepts

PJ – Peta Joules ($*10^{15}$)

TJ – Tera Joules ($*10^{12}$)

GJ – Giga Joules ($*10^{9}$)

MJ – Mega Joules ($*10^{6}$)

The MuSIASEM approach

MuSIASEM or **Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism** is a transdisciplinary approach developed for studying sustainability issues building on energetics, biophysical economics using insights from complexity such as relational analysis, cybernetics, semiotics, hierarchy theory and general systems theory. The approach was introduced by Mario Giampietro and Kozo Mayumi at the end of the 90s and it is under continuous development.

The multiscale and transdisciplinary approach proposed by MuSIASEM uses relational analysis for the quantitative assessments considering diverse potentially relevant types of expertise, legitimate interest and concern when informing policy making. MuSIASEM can be used as a decision support tool for diagnostic evaluation or option space exploration in a transparent way. Sustainability of social-ecological systems can be evaluated in relation to three complementary key aspects:

- (i) Feasibility - the compatibility with processes outside human control taking place in the biosphere (external biophysical constraints);
- (ii) Viability - the compatibility with process under human control in the technosphere as available technologies or the existence of adequate social practices;
- (iii) Desirability – the compatibility with normative values and institutions such as cultural traditions, established social practices or preferences.

MuSIASEM has been used in the EUFORIE project to provide a critical appraisal of the actual framing of the concept of efficiency in political and scientific arenas from a conceptual and practical point of view. We propose an alternative conceptual tool: the End Use Matrix, which breaks down silos and prevents the most powerful actors from cherry picking the specific output/input ratios, among the many possible indicators of energy efficiency, that best matches their agenda. To achieve the goals of saving energy and associated environmental impacts such as emissions of GHG, efficiency policies should be based on effective indicators establishing a clear relation between the local performance of energy uses and absolute energy consumption, i.e. global performance of the whole network of energy conversions. Establishing this relation requires developing a system of accounting capable of maintaining coherence across scales and dimensions of analysis while combining different metrics.

For more about MuSIASEM, see:

Giampietro, M. and Mayumi, K. 1997. A dynamic model of socioeconomic systems based on hierarchy theory and its application to sustainability. Struct. Chang. Econ. Dyn. 8, 453–469. https://doi.org/10.1016/S0954-349X(97)00017-9

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

Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy analysis for a sustainable future: multi-scale integrated analysis of societal and ecosystem metabolism. Routledge, New York.

The End Use Matrix

The end use matrix is a MuSIASEM tool that integrates information on where, how, how much, which type, who and why biophysical funds and flows are used in a socio-economic system. The analysis is not deterministic but still it makes it possible to generate contingent evaluation of the viability of alternative profiles of allocation of human time or other resources, in relation to a set of functions to be expressed by society. It organizes quantitative information referring to different end uses described across different levels of analysis (whole society, sectors, sub-sectors). It follows the fund-flow scheme of Geoergescu-Roegen, where flows are quantities appearing or disappearing over the period of the analysis: energy, money, water, etc., and funds are structural elements preserving their identity: workers, technical capital, land use.

An *end use* is defined as the specific profile of inputs required to achieve a specific task. In the simplified definition adopted in this example, considering energy inputs only, the expected profile of inputs required for achieving a given task i can be represented using a vector:

$$[HA_i,\ EMR_{electricityi},\ EMR_{heati},\ EMR_{fueli},\ ET_{electricityi},\ ET_{heati},\ ET_{fueli}\ ]$$

where:

- **HA_i** - Human Activity allocated in hours/ year (h);
- **ET_{ji}** - Energy throughput metabolized in the form of energy carrier j. In this case the index j refers to electricity, heat or fuel, in joules/year (J);
- **EMR_{ji}** –Exosomatic Metabolic Rate: the amount of energy carriers metabolized per human activity, measured in joules of EC_j per hour of HA_i (J/h) for the different typologies of energy carrier. It is a proxy of use of technical capital.

The combination of extensive variables (HA_i and ET_i) and intensive variables (ET_i/HA_i – EMR_i) in different levels generates redundancy in the information space because of three basic congruence constraints, what is called a sudoku effect:

$$\#1\ (\Sigma ET_i)_{level\ n\text{-}1} = ET_{j\ level\ n};\qquad \#2\ (\Sigma HA_i)_{level\ n\text{-}1} = HA_{j\ level\ n};\qquad \#3\ HA_i{\cdot}EMR_i = ET_i$$

This entails impredicative relations. What society wants to satisfy human needs defines a downward causation, whereas the effects of the constraints determined by a limited amount of resources, technology or labor, generates an upward causation. This defines the option space within which political decisions can stir the metabolic pattern.

EU28 Year 2015	Human Activity HA (h p.c./year)	power capacity EMR$_{elect}$ (MJ/h)	EMR$_{heat}$ (MJ/h)	EMR$_{fuel}$ (MJ/h)	energy carriers ET$_{elect}$ (GJ/year)	ET$_{heat}$ (GJ/year)	ET$_{fuel}$ (GJ/year)
Whole society *Level n*	8,760	2.6	4.7	3.8	23	42	34
Household	8,028	0.7	1.8	1.8	6	15	14
Paid Work *Level n-1*	732	2.6	4.7	3.8	17	27	20
Services & Government	531	12	11	32	6.3	5.9	17.1
Manufacturing & Construction	161	42	91	5	6.7	14.7	0.8
Energy & Mining	7	485	785	29	3.4	5.5	0.2
Agriculture *Level n-2*	41	10	15	27	0.4	0.6	1.1

The definition of an end use matrix allows a non-deterministic analysis of the constraints affecting the allocation of human activity on a set of competing functional compartments of the society – i.e. there is a chicken-egg relation over the values taken by the numbers in the matrix. The analysis is not deterministic but still it makes it possible to generate contingent evaluation of the viability of alternative profiles of allocation of human time or other biophysical resources, in relation to a set of functions to be expressed by society.

For more about the End use Matrix see:

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.

The Sudoku Effect

Sudoku is a logic-based number placement puzzle consisting in a 9x9 grid with digits so that each column, row and each of the nine 3x3 sub-grids that compose the grid, contains all the digits from 1 to 9. The column, row and block constraints generate mutual information within the information space of the sudoku grid. As a result, each time a number is introduced in the grid a path dependency is generated, and the option space of viable patterns is reduced. The sudoku game provides a very direct example of how relational analysis – the pre-analytical definition of expected relations over the values that will be taken by numbers in a specified grammar – can be used to generate an impredicative effect within an information space. A sub-critical Sudoku, in which the written numbers still does not fully define the missing ones, is an example of set of quantitative relations that is not deterministic, but still providing enough mutual information to generate expected patterns (Giampietro and Bukkens, 2015).

In MuSIASEM, the Sudoku effect refers to the mutual information generated when building a multi-scale and multi-dimensional set of relations over the quantitative assessments of flows and flow-fund relations. This mutual information generates constraints determined by the impredicative relation between top-down and bottom-up information. Therefore, aggregated data from statistical sources must be consistent with technical data about the processes described at lower hierarchical levels. The Sudoku effect makes it possible to apply systematically what is called triangulation in evaluation science, a "*research technique that facilitates the cross-verification using more than two sources. In particular, it refers to the application and combination of several research methodologies in the study of the same phenomenon […]. By combining multiple observers, theories, methods, and empirical data, researchers aim at overcoming the weaknesses, intrinsic biases and the problems that are often found in single method, single-observer and single-theory studies*." (Carugi, 2016).

When describing the metabolic pattern of a society with MuSIASEM we can characterize the various activities of both production and consumption in the form of a data array. The data are composed both of extensive variables – quantities of energy of different forms and quantities of human activity – and intensive variables – ratios of quantity of energy per unit of human activity. The need of reaching congruence across the values describing the metabolic pattern across different levels of analysis becomes extremely transparent in the organization of data in the end use matrix (see the box presenting the end use matrix).

For more about the Sudoku Effect see:

Giampietro, M., Bukkens, S.G.F., 2015. Analogy between Sudoku and the multi-scale integrated analysis of societal metabolism. Ecol. Inform. 26, 18–28.

Technical summary

The goals of this deliverable

Deliverable 4.1 (produced within the activities of Workpackage 4) focuses on the problematic use of concept of efficiency in the analysis of the performance of the economic process and explores possible solutions to be adopted to develop more effective methods to characterize the performance of the use of energy in modern economies. To achieve this goal, we adopt basic principles of energetics and the accounting framework of Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). The text of Deliverable 4.1 has two goals:

(1) clarify the innate ambiguity associated with the concept of efficiency making problematic the quantitative definition of efficiency targets. The analysis presented here identifies the epistemological problems associated with the concept of energy efficiency, and it provides the theoretical basis used in the second deliverable – Deliverable 4.2 - to propose an alternative approach - the end use matrix – associated with the concept of "energy performance". Therefore, this deliverable deals with conceptual issues such as: What is the proper definition of energy efficiency for a society? Is the same definition be used for a refrigerator, an industrial process, an economic sector? If this is not the case, what are the differences that should be considered for defining "efficiency" at different scales? How robust and useful are the definitions (and the targets) used right now? Can we use the semantic message of "increasing efficiency" in a more effective way (by adopting a more articulated concept of energy performance – i.e. using a set of indicators that have to be tailored to specific situations) rather than just calculating a ratio between two numbers – an output over an input - "one size fits all"? This epistemological discussion is important because the ambiguity found in the possible interpretations of the concept of "efficiency" translates into a proliferation of targets – referring to different dimensions and different scales – and indicators that are not only theoretically incorrect, but also misleading for the selection of sound policies. To discuss energy policy it is necessary to have the ability of contextualizing and scaling up the effects that a change in "efficiency" in a specific part of the economic process has when considered at level of the whole. This is not done at the moment. Therefore, the first goal of this deliverable is to introduce a few theoretical concepts derived from energetics and adopt the MuSIASEM accounting framework to show the need of developing a more effective package of indicators that can be used to apply the concept of "efficiency";

(2) illustrate a framework of quantitative analysis that can be used to characterize the performance of the energy sector of EU countries based on a standardized representation of the set of energy transformations taking place in it. This characterization makes it possible to individuate the factors that should be studied to explain relevant differences in the performance of the energy sectors of EU countries. In particular it makes it possible to quantify three distinct factors affecting the performance of an energy sector:

(i) the advantage given by "externalization" through import of both Primary Energy Sources (PES) and Energy Carriers (EC) – e.g. importing electricity makes a society "more energy efficient" than producing that electricity after having mined and powered a coal power plant. But this improvement is independent of the "technical efficiency" of the technology used;

(ii) the role that the mix of PES plays in determining the performance of the energy sector (affecting the characteristics of the overall conversion PES → EC) – e.g. producing electricity with hydropower sources reduces GHG emissions when compared with coal fired power plants. But this improvement is independent of the "technical efficiency" of the technology used;

(iii) the importance of considering the specific mix of EC required by society – i.e. the mix of quantities of electricity, fuels and process heat used by a society is determined by the profile of end uses in the other sectors of the economy. That is, it depends on the mix of socio-economic activities, carried out both in the household and paid work sector, needed for reproducing the society and guaranteeing a desirable standard of living to the population. Reducing emissions by focusing on financial activities reduces emissions. But this improvement is independent of the "technical efficiency" of the technology used.

The quantitative analysis carried out in this deliverable refers only to the biophysical transformations of energy forms taking place in the energy sector. That is, Deliverable 4.1 deals only with the analysis of the two functions expressed by the energy sector:

(1) how Primary Energy Sources (e.g. coal, oil, wind, solar radiation, uranium, etc.) are extracted or imported by EU countries; and

(2) how these Primary Energy Sources are converted into Energy Carriers (electricity, fuels, process heat) used by the economy.

The analysis of the economic uses of the energy carriers consumed by a society: what are the final end uses of energy in the economy is provided in Deliverable 4.2. There we will study the nature of the energy services obtained in the economy when transforming an input of energy carriers into an output of useful work and how these energy services relate to the generation of the Gross Domestic Product.

The content of this deliverable

The text of the deliverable is divided into two sections:

Section 1 provides an epistemological discussion of the concept of "energy efficiency". This discussion flags the impossibility of using this simplistic concept to generate a single indicator of performance "one size fits all". To make this point, it provides a series of examples of conceptual and practical problems indicating the need of abandoning the simplifications associated with reductionism. The "performance" of a set of energy transformations has to be characterized using an integrated set of indicators referring to different scales and dimension of analysis. In turn, this requires the adoption of a logical framework (MuSIASEM – presented in Section 2) capable of defining the different scales considered in the analysis of sustainability – the boundary of the system (the level of openness of the energy sector), and the duration (the time horizon) of the analysis. When framed in this way, any robust analysis of "efficiency" of the energy sector of a country should consider simultaneously two different aspects of performance that can only be observed at two different levels of analysis:

1. At the level of the energy sector – systemic characteristics of this sector should include: (i) what is the mix of energy systems (mix of conversions PESi ? ECi) determining the overall supply of the mix of ECi to society; and (ii) what is the level of openness of the energy sector. This information is required to assess how important are: (i) the performance of the domestic production – carrying out the extraction of PES and conversion of PES into EC; compared with (ii) the effect of the terms of trade (import vs export). The combination of "domestic supply" and "imports" determine the overall efficiency of the conversion of PES into EC at the level of the energy sector. A very inefficient technology used in the processes determining the domestic supply of PES and EC can result completely irrelevant for the energetic efficiency of an economy in the case 99% of the PES and EC are imported;

2. At the level of individual energy systems (within the energy sector) – the performance of the energy system is determined by the profile of inputs/outputs of the different functional processes – e.g. extraction, transportation, refinery, electricity production – taking place in the energy system;

In this way it becomes possible to study simultaneously across different levels of analysis and scales: (i) the performance of the whole energy sector; (ii) the performance of individual energy systems (e.g. coal powered electricity production, hydroelectric production, oil sector); and (iii) the performance of typologies of plants operating in the energy systems (the technical coefficients of a small/large coal powered plant, small/large hydroelectric production plant, etc.). It should be noted however, that this result can only be obtained after acknowledging the fact that this integrated analysis requires integrating data coming from different sources of information, because the standard set of data found in statistics at times do not provide the required input (Giampietro and Sorman, 2012). The performance of functional compartments – e.g. the energy sector - described at the large scale, can only described using top-down data (derived from statistics), whereas the performance of individual plants – e.g. a refinery - described at the local scale, can only be described using bottom-up data (derived from technical coefficients).

Section 2 illustrates practical aspects of quantitative analysis used to characterize the performance of the energy sector of EU countries using examples of applications of an accounting scheme based on the concept of societal metabolism (MuSIASEM).

After providing an overview of the MuSIASEM approach it introduces the quantitative analysis of the performance of the energy sector of EU 28. This analysis is based on the concept of processor (developed in relational analysis) and makes it possible to establish a bridge across different scales and different dimensions of analysis. This analysis makes it possible also to deal with the effects of externalization (import of PES and EC) on the performance of the energy sector over EU countries.

Practical applications of MuSIASEM are used to show the possibility of assessing the amount of energy carriers, labor and CO2 emissions saved because of imports. However, these applications also flag the existence of systemic problems faced when trying to carry out this analysis using only information coming from energy statistics (this point is discussed further in Deliverable 4.2). The solution suggested to avoid these problems is to integrate the information coming from statistics with information coming from the analysis of the technical coefficients of power capacity (e.g. the representation of the performance of the plants in charge of the energy transformations).

The section discusses then the advantages of moving away from a strategy of analysis based only on considering flows (what is done right now). The approach to energy analysis used right now, based on the tracking of flows, implies that the definition of targets and policies is formulated in relation to characteristics of flows – e.g. we should reduce inputs, reduce emissions, increase output/input ratios). The proposed alternative is a strategy of analysis based on the flow-fund model proposed by Georgescu-Roegen in which the flows are never considered in isolation but always considered as a consequence of an existing structure of relations and the characteristics (and quantity) of fund elements. For example, a flow of electricity (a given quantity of kWh) can only exist as a connection between: (i) a given amount of power capacity operating in the energy sector (the power plant) determining the quantity, timing and pace of the supply; and (ii) a given amount of power capacity operating in the rest of the economy (the end users of electricity) determining the quantity, timing and pace of the requirement. In this way, it becomes much easier to understand the problems of the energy sector – in the given example the factors determining the performance of the electric grid.

Findings and policy recommendations

The Problematic use of the Concept of Energy Efficiency for Policy

The efficient use of energy is recognized as a key pillar of energy policy in the EU. Indeed, the "energy efficiency first" principle is at the heart of the Energy Union strategy and energy efficiency sits alongside GHG reduction ambitions and renewables targets as part of the EU's overall climate and energy policy package (European Commission, 2016). However, despite its prominent role, as discussed below, relatively little academic attention has been paid to the definition and quantification of the concept of 'energy efficiency'. The quantification of the concept of 'energy efficiency of the economy' brings along epistemological problems. Energy efficiency is only one of many relevant factors that impact the energy performance of complex systems. For instance, we do not commonly define the performance of a car by its mileage only (the efficiency in fuel use). Fuel efficiency must be contextualized in order for it to have meaning as an indicator of performance. That is, what is an acceptable level of fuel consumption depends on many factors, such as the size and comfort of the car, the load to be carried, the required speed, the price we want to pay, or the expected durability. We generally do not compare the performance of a sedan, a sport utility vehicle, a van and a truck on the basis of one simple, 'one size fits all' output/input ratio.

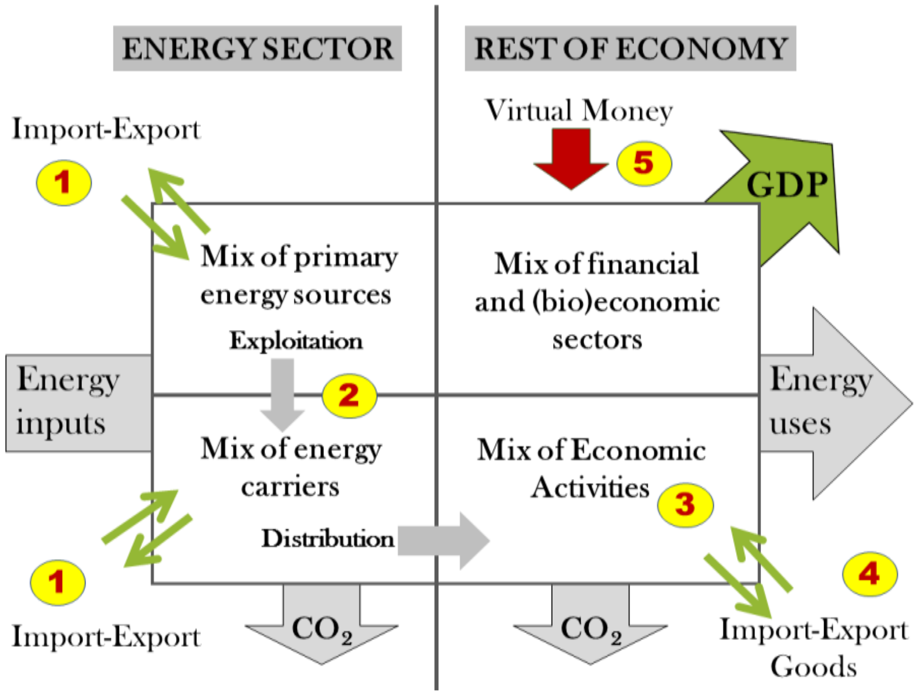


Figure 1 Factors affecting the energy and carbon intensity of an economy

The same applies to the energy performance of a country (a much more complex system than a car). Using simple ratios such as the economic energy intensity (energy consumed/GDP) or economic emission intensity (emissions/GDP) carries the risk of comparing apples to oranges. A meaningful interpretation of these two ratios at the national level requires us to carefully consider the implications of the following five factors (Figure 1):

(1) energy imports – when importing energy - both Primary Energy Sources (oil, natural gas or coal) or Energy Carriers (e.g. electricity or fuels) – countries are externalizing to other countries their consumption of energy for extraction, refining and power generation. Therefore, a country importing 1 kWh of electricity will result "more efficient" in terms of energy consumption and emissions than a country producing that kWh at home. This independently of the "efficiency" of the technology used;

(2) the specific mix of primary energy sources and energy carriers – a country having 95% of its electricity from hydropower (e.g. Norway) will have a lower consumption of primary energy than a country having 90% of its electricity from coal (e.g. Poland). These differences are not due to a better "efficiency" of the technology used to generate electricity;

(3) the specific mix of economic activities – in the same way an economy based on financial operation (e.g. Hong Kong) will result less energy intense (and generate less emission) per unit of GDP of an economy based on industrial production (e.g. P.R. China). Also in this case the "efficiency" of the technology used in banking or in the industrial sector (the same in the two examples) has nothing to do with the difference in the consumption or emissions of the economy per unit of GDP;

(4) the terms of trade favoring externalization of energy intensive production processes – this is another factor making it possible for an economy to reduce its energy intensity and lower the level of emissions per unit of GDP. Energy and material intensive goods can be imported rather than produced reducing consumption and emissions;

(5) 'virtualization' of the GDP through credit leverage and quantitative easing – in the same way a massive use of credit leverage (supported by quantitative easing) can be used to sustain the GDP of a country relying on imports to sustain its internal consumption. In this case, independently of changes in the efficiency of the biophysical processes a massive use of credit to import products will result in a decrease of consumption and emissions.

Key findings

Energy efficiency is a simplistic indicator

The analysis presented in the deliverable suggests to abandon the idea of adopting a simplified quantification (monocriterial index) of energy efficiency for moving to the concept of energy performance (multi-criteria characterization)

Modern economies are complex metabolic systems that consume energy inputs and generate emissions in order to express their functions. In scientific technical jargon they are called self-reproducing open adaptive systems, that are organized over different hierarchical levels. This characteristic makes that economies cannot be observed and represented on the basis of only one single scale or dimension of analysis at the time. Given that energy efficiency is a mono-criterial concept (a simple output/input ratio), it is too simple if we want to assess the energy performance of a modern economy. An economy does not use "energy" generating "emissions" – the different processes taking place in the various sectors and sub-sectors of the economy: (i) use specific typologies of energy (electricity, fuel and process heat) to carry out specific typologies of tasks (the delivery of goods and services); and (ii) generate specific types of emissions (a set of GHG) and pollutions, depending on the nature of the processes. At the level of the national economy, the use of the indicator energy efficiency does not make sense to study the effect that technological changes have on the decoupling of economic growth and energy use (and carbon emissions) because it cannot identify the role that changes in the mix of inputs and processes have on the overall assessment. When applied to specific energy transformations at the local scale, it can only provide a partial assessment and it requires a complex process of scaling, tailored to the specific characteristics of the system, to become relevant at the level of the whole system. Policy targets based on the adoption of the concept of energy efficiency – definitions of input/output ratios – rely on an analysis that is based on the measure of flow/flow ratios. This choice is not effective when the value of these ratios is determined by a combination of multiple factors that have to be observed at different scales of analysis. Indeed, the same value of the input/output ratio can be generated by different combinations of lower-level factors. The adoption of too simplistic indicators of performance to define policy targets is likely to result into poor results in relation to the expected goals of the policy.

When dealing with the complexity of the concept of performance the problem becomes how to integrate across levels, scales and dimensions different quantitative assessments based on the adoption of different descriptive domains. For this task it is essential to identify the factors that have to be considered to study and compare the performance of economic (and sub-economic) sectors.

Complex Energy Metrics require the adoption of the rationale of metabolic analysis of energy transformations

The complexity of the metrics of energy accounting represents another problem. There are three non-equivalent ways of accounting energy, all of which are needed to assess the performance of an economy: (1) primary energy sources (e.g., coal, wind, hydro, oil); (2) energy carriers (e.g., electricity, fuels, process heat); and (3) energy end-uses (quantitative characterization of what is achieved by the use of energy). In addition, we need to distinguish between two different energy forms (qualities), thermal energy (e.g., MJ of fuels) and mechanical energy (e.g., kWh of electricity), for both primary energy sources and energy carriers. Often these distinctions are not (properly) used in the development of policy targets and policy evaluations. Without using these distinctions becomes problematic to have an effective analysis of the changes that a policy can generate when considering different criteria of performance.

The rationale of metabolic analysis makes it possible to associate a flow of energy (e.g. a given amount of food or a given amount of gasoline) to a given fund element (e.g. a person or a car) used to fulfill a goal (e.g. surviving or driving to a given destination). In this case, we can make the representation of a quantity of energy (a flow) much richer by contextualizing its assessment in relation to two converters – i.e. the fund that has generated the flow and the fund that uses the flows – and in relation to a task. For example, if you have a given quantity of food energy you must have a fund that produced it (e.g. hectares of cropland) and a fund that is consuming it (e.g. dietary intake of people), the same applies to electricity a fund that produced it (e.g. a nuclear power plant) and a fund that uses it (e.g. the appliances in the residential sector). Assessing the network of energy transformations using a combination of flow-fund relations provides a much more robust understanding of the problems than just discussing in terms of flows. For examples, when dealing with electricity, an assessment of kWh of "electricity" produced or consumed is not useful. Electricity has to be divided in "base load electricity" (constant production difficult to change in pace), "peak electricity" (adjustable production of electricity when needed) and "intermittent electricity" (randomly producing electricity independently of the requirement). Intermittent electricity may produce when it is not needed or may not produce when it is needed. Therefore, assessing the power capacity of this type of electricity source – the size of the fund elements used to generate the supply – is not a particularly relevant piece of information. Yet this is one of the most popular indicators used to assess the size of this source of electricity.

Policy Recommendations

The discussion of energy policies should no longer be based on scientific evidence based on quantitative assessments determined using the simplistic concept of efficiency (unable of handling multi-scale analysis). Quantitative evidence should be based instead on the concept of multi-level energy performance (multi-criteria and multi-scale analysis).

The adoption of the rationale of the metabolic pattern can dramatically help the tracking of flows of energy carriers looking at the two interfaces: (i) what type of funds (e.g. power plants, distribution infrastructure) are required in the energy sector to produce the different types of energy carriers – depending of the given mix of primary energy sources; and (ii) what type of funds (e.g. cars, trains) are required in the other compartments of the society to use energy carriers to do what. The rationale of metabolic patterning allows one to identify which energy carriers are used by specific societal compartments and then to associate them with specific societal functions.

The definition of targets for improving the energy performance of the economies should be based on insights derived from an integrated analysis across different levels of organization. This requires:

1. An effective characterization of the energetic metabolism [dealing with 4 points: (i) what type of energy is used; (ii) how is it used; (iii) which sectors are using it; (iv) why is used]; and

2. An effective characterization of the degree of openness of the various sub-sectors [assessing the effects of externalization on their local performance]. This better quantitative characterization can be obtained by adopting the analytical concepts provided by MuSIASEM: processors, power capacity, utilization factors and the distinction between domestic and imported supply of both PES and EC.

An integrated analytical tool combining these concepts and providing a solution to this challenge is presented and illustrated with examples in Deliverable 4.2.

Tasks of this deliverable related to WP4

Task 4.1. External view of energy systems

The MuSIASEM approach can look into the external constraints limiting the supply of the required energy inputs and characterize the performance of individual energy systems used for the exploitation of specific primary energy sources and the overall performance of the energy sector. For doing so, different production factors (power capacity of different types, human activity and land uses) will be investigated and so will the subsequent impacts created from the pressure on the environment.

Task 4.3. Using the MuSIASEM as a decision-making tool for creating options in terms of feasibility, viability and desirability for energy systems

This multi-scale integrated analysis can be used as a tool for assessment and decision-making in understanding how different forms of energy carriers are used to perform different societal tasks, and to look into the external constraints limiting the supply of the required energy inputs. These can thereafter be used to elaborate upon options of feasibility and biophysical viability as well as desirability to take action in terms of energy efficiency.

SECTION 1 The concept of "efficiency" is simplistic and unreliable when used to develop targets and indicators

1.1 The problematic use of narratives based on energy efficiency for selecting policy

The popularity of the term "efficiency" in policy discussion can be explained by considering two key aspects:

(i) The concept of efficiency is extremely flexible thanks to its innate semantic ambiguity. The adjective *efficient* is generally used as a synonym of "better" and can be applied to everything. An efficient a city is better than an inefficient city. The same applies to an efficient storage of information or an efficient cataract surgery. The problem with the use of the term efficiency starts when trying to measure "how much better" the city, the storage of information or the cataract surgery is. This combination of being flexible and being considered "by default" a valid normative indicator (we should always increase efficiency "no matter what") makes the use of this concept extremely dangerous.

(ii) The innate ambiguity of the term efficiency remains even when we try to frame it in technical terms, e.g. in engineering or in physics. When measuring the efficiency of a windmill, the assessment of efficiency refers to a dimensionless ratio in which the output and the input are measured in the same unit of measurement - mechanical energy output (electricity)/mechanical energy input (kinetic energy of the wind). However, when measuring the mileage of a car (the efficiency in the use of fuel) the ratio miles/energy consumed is no longer dimensionless. The output is a quantity mapping onto mechanical work, the input is a quantity mapping onto potential chemical energy. Moreover, in physics or engineering efficiency is used to measures a quantity of useful work (without a time dimension) in relation to the quantity of energy used (without a time dimension). In this way, using imaginary thermodynamic cycles, referring to processes requiring infinite time durations, it was possible for the pioneers of thermodynamics to establish a standard value of efficiency for a thermal engine, while focusing on a limited set of variables. The efficiency of "ideal" thermodynamic cycles was then used to measure the efficiency of real thermodynamic cycles. However, nobody wants to drive a car with an engine that requires an infinite time to move the car to another place. This implies that as soon as the trade-off "efficiency" vs "power" (determining the time required to do the work) is included in the analysis, then it becomes impossible to have a single indicator of performance in terms of output/input. The efficiency becomes a function of the power level: the mileage of a car – the efficiency in the use of gasoline - depends on the speed at which we want to drive – the power output provided by the engine.

In any case, the ambiguity associate with the term "efficiency" is so high that makes it possible for the term to be used both in a vernacular and scientific context. This is how efficiency became an indicator of performance – e.g. an energy target. In this way, one gives the impression to that the resulting information is useful and "scientifically sound" and that therefore it can be trusted. No wonder that policy discussions and policy recommendations tend to heavily rely on the concept of "efficiency" to establish normative targets. By relying on the credibility given by the field of thermodynamics those proposing “efficiency” indicators assume that it is possible to tame and measure the elusive concept of performance in the field of energy governance. In relation to this point it should be noted that Carnot himself, the father of thermodynamics, concluded his seminal book (the book in which he “invented” the scientific definition of *thermodynamic efficiency*) exactly by warning the reader against this delusion. In the closing paragraph of his *Reflections on the motive power of fire, and on machines fitted to develop that power* (Carnot, 1824) he states:

> “*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 more harmful than useful if they caused other important considerations to be neglected. The economy of the combustible [**efficiency**] 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. To know how to appreciate in each case, at their true value, the considerations of convenience and economy which may present themselves; to know how to discern the more important of those which are only secondary; to balance them properly against each other; in order to attain the best results by the simplest means; such should be the leading characteristics of the man called to direct, to co-ordinate the labors of his fellow men, to make them co-operate towards a useful end, whatsoever it may be*” [p. 59 emphasis added].

As suggested by Carnot, the complexity of the concept of efficiency requires generating a variety of “performance indicators”. It should be noted that Carnot is warning us about the potential pitfalls of an excessive simplification of the characterization of the performance of an engine! IF it is unwise to assess the performance of an engine using just an indicator of performance – efficiency – THEN let alone try to assess in the same way the performance of an energy system, or even worse the whole energy sector, or even worse the whole economy. In spite of the wisdom of Carnot very often the framing of the policy aimed at increasing the performance of the use of energy in the economy are based on very simplistic indicators of “energy efficiency” based on a simple ratio of two numbers.

The rest of Section 1 illustrates with practical example the epistemological problems found when trying to use the concept of “energy efficiency” to characterize in quantitative terms the performance of the energy metabolism of society.

1.2 The fatal attractor: the mixing of “energy efficiency” with economic analysis

The new Energy Efficiency Directive (2012/27/EU – EED) has an “energy efficiency target” of reducing by 20% the Unions Primary energy consumption by 2020. However, this target is about reducing the consumption of the input. According to this target a total implosion of the EU economy in the year 2020 determining a reduction of 80% of Unions Primary energy consumption would be considered as a spectacular success in increasing the “efficiency” of the EU economy. As a matter of fact, commenting the downward trends of emissions in 2008 the European Environment Agency claimed that "our policies and tools seem to be working" https://www.eea.europa.eu/media/newsreleases/eu-greenhouse-gas-emissions-more

However, a different explanation of the phenomenon is given by the graph in Figure 2.

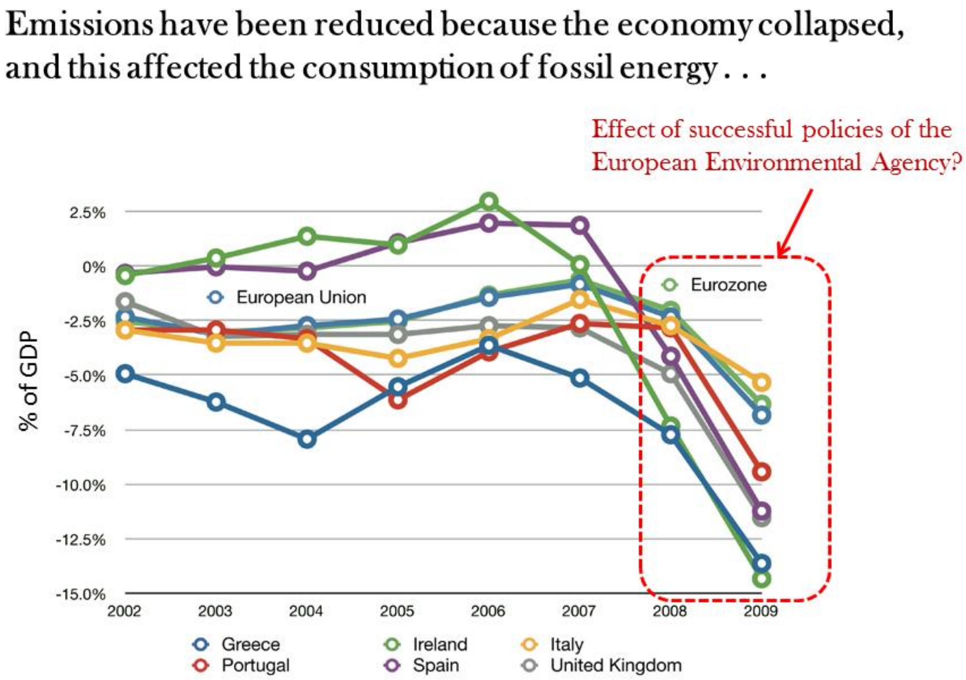


Figure 2 An alternative explanation for the reduction of emissions in EU in 2008/2009

The obvious problem flagged by this example is that the target of a reduction of 20% has been defined only in relation to a change in the input, whereas the concept of "efficiency" requires considering the relation between an output and an input! In this case the output should be "what is generated by the economy" and the input should be "the consumption of primary energy consumption". Therefore, if one adopts an "energy efficiency target" of reducing by 20% the Unions Primary energy consumption by 2020 one must also assume that "what is generate by the economy" will remain the same in 2020 and remain unaffected by the reduction of energy. Only in this case - maintaining the same output with less input – such a reduction could be interpreted as an increase in efficiency. But then how to know whether the economy will generate the same output in 2020? This is the reason for the use, as indicator of efficiency, of the Economic Energy Efficiency indicator. This is the ratio between: (i) GDP of a country (supposed to measure the economic performance of a country) – the output achieved; and (ii) Primary energy consumption of a country – the input used. Then, after calculating the ratio between: (i) how much is the GDP of a country; and (ii) how much energy has been used to generate GDP; we can say that the lower is the quantity of energy used per unit of GDP the "more efficient" is the economy of the country. According to this narrative we can use the EEI index as an indicator useful to assess the economic energy efficiency of countries. Unfortunately, this narrative and the consequent choice of indicator is useless for three important reasons explained in the next two subsections.

1.2.1 At the level of whole countries the EEI index is not useful for comparing countries

The ratio EEI defines a numerical value expressed in MJ/€ (Mega Joules of energy per € of GDP referring to a given year). This EEI ratio can also be written as a ratio of two ratios:

(i) "Energy used per capita in a year" – this value is obtained by dividing the Total Energy Throughput per year (TET) by the Total Human Activity in a year (THA = population size times 8760 hours/year). This ratio is measured in MJ/h; and

(ii) "GDP per capita per year" – this value is obtained by dividing the Gross Domestic Product per year (GDP) by the Total Human Activity in a year (THA = population size times 8760 hours/year). This ratio is measured in $/h.

EEI = "TET/THA" **/ "**GDP/THA"

The analysis of the relation between the numerical values taken by these two ratios shows the weakness of this indicator –Figure 3. Both the nominator and denominator of the EEI ratio are good indicators of development: (i) a country with either 20,000 € p.c./year and/or 260 GJ of energy p.c./year is a developed country; whereas (ii) a country with either 2,000 € p.c./year or 26 GJ of energy p.c./year is a developing country. However, these two values (energy use per capita and GDP per capita) are within the range of expected characteristics (benchmarks) of the metabolic pattern of developed countries, and **they are strongly correlated**.

For this reason, these two couples of values tend to be correlated - in the chosen example (i.e. Finland and El Salvador in 1997) the value of EEI for both is exactly the same:12.6 MJ/$ - and therefore the EEI index based on ratios of two correlated variables is void of external referent (Giampietro et al. 2012). The use of this indicator cannot even detect difference in the dynamic of change: in the period 1998-2004 El Salvador did not change the values of both TET/THA (MJ/h) and GPD/THA ($/h), whereas Finland in the same period have

changed both values quite significantly. However, the ratio over the two values remained the same.

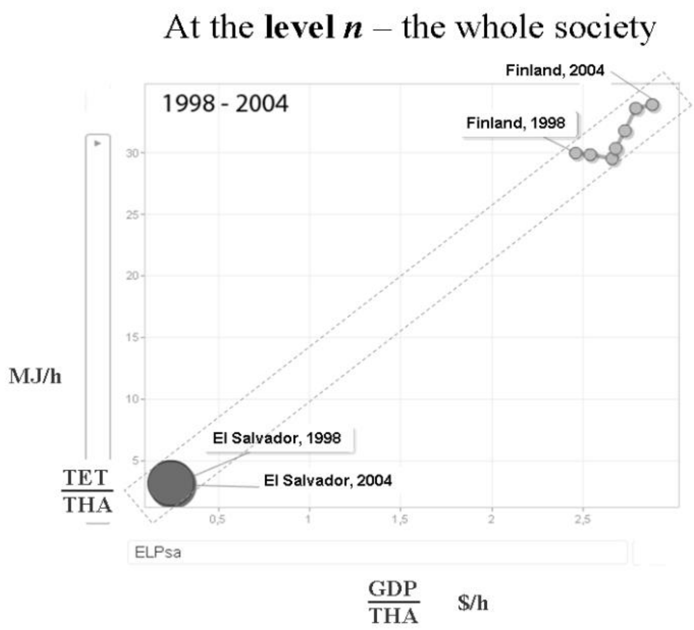


Figure 3 Visualizing the relation of the two variables determining the value of Economic Energy Intensity: TET/THA (MJ/h) and GPD/THA ($/h) – After Giampietro et al. 2012

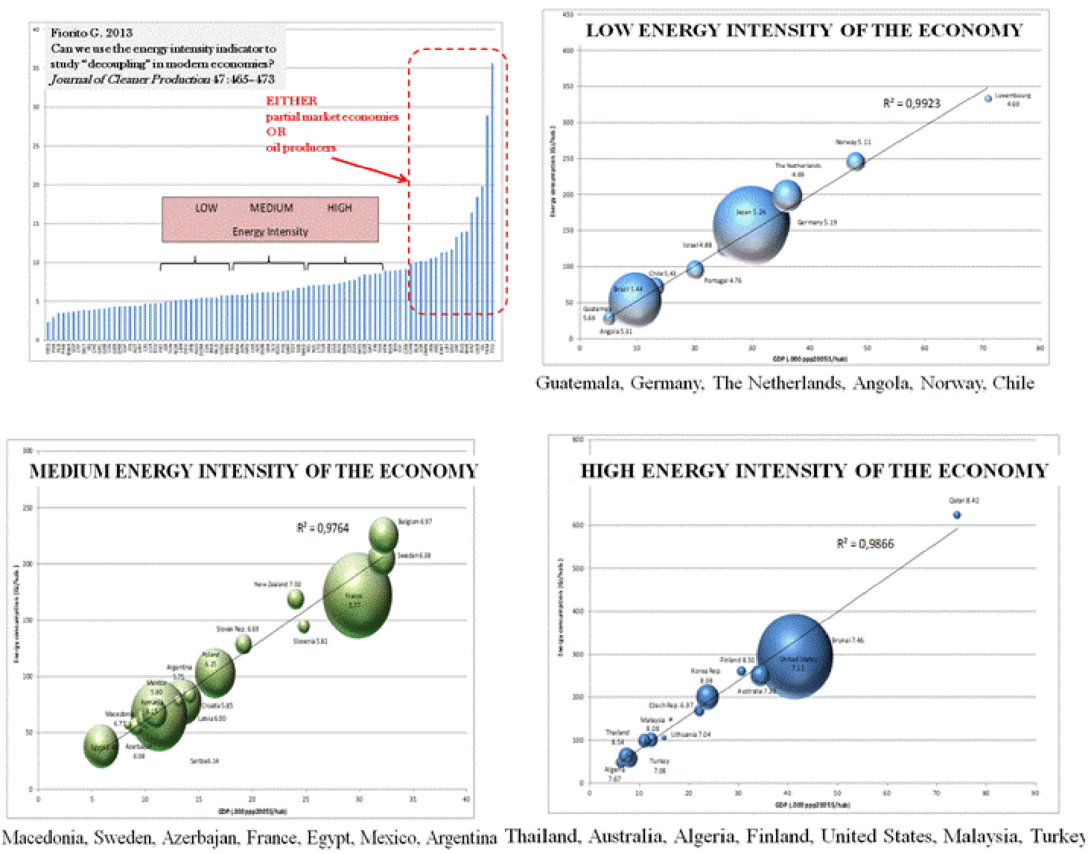


Figure 4 – Upper left graph – values of EEI for the different world countries; Other graphs –clusters of countries with very close values of EEI (Fiorito, 2013)

It should be noted that the case of Finland and El Salvador is not a special coincidence. On the contrary, looking at all the countries of the world we find exactly the same situation of correlation over the two component of the ratio EEI. This fact has been explored by Fiorito (2013) and it is illustrated in Figure 4. This means that when studying differences in the value of the EEI index across different countries, while carrying out this analysis at the level of the whole economy, when dealing with non-oil exporting countries, we are studying differences that are found in a cloud of data representing white noise.

In fact, the discriminating power of this indicator can just spot oil exporters, economies consuming large quantities of energy for extracting and refining the oil exported to the rest of the world. The non-oil-exporting countries, especially those expressing the typical pattern of modern economies do have values of EEI quite similar.

1.2.2 In order to individuating factors explaining differences in the energy intensity of the economy one has to move to a lower level of analysis (at the level of economic sectors)

To avoid this problem, it is necessary to open the black box of the economy seen at the level of the whole society and look inside at the characteristics determining the EEI of its internal components – e.g. the paid work sector, that can be disaggregated into various sectors such as industry, service sector, and agriculture. An example of this analysis is illustrated in Figure 5.

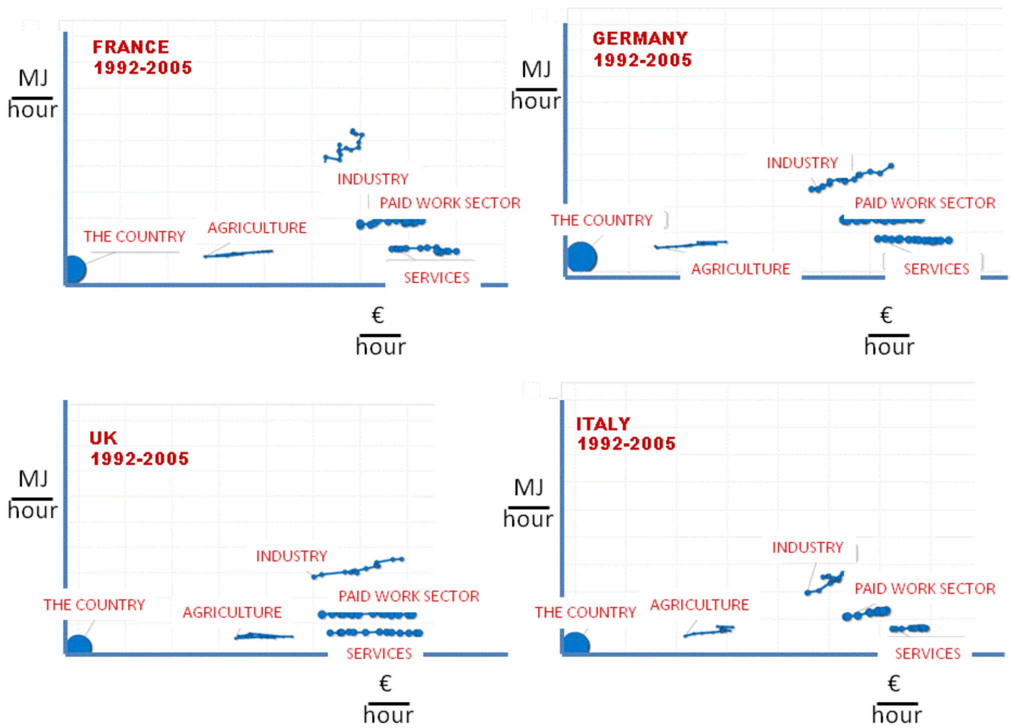


Figure 5 – Examples of blueprint of EEI for the different economic sectors of EU countries in the time window 1990-2005 (Giampietro et al. 2012)

In this way we can see that different compartments of the economy have quite different levels of energy intensity once normalized per hour of human activity. For example, the industrial sectors of EU economies operate at a value higher than 300 MJ/hour of work whereas the service and government sectors operate at a value of around 100 MJ/hour of work. When looking at the amount of sectoral GDP produced by these sectors per hour of labor one can see that in the last decade the industrial sector had to increase energy consumption to increase its sectoral GDP (and not always with success in all countries). On the contrary the service and government sector has increased its sectoral GDP without increasing energy consumption.

How to explain this difference? Has the difference in "economic energy efficiency" of these two sectors (industry vs services) been determined by major technological improvements in the way the service sector operates when compared with the industrial sector? Unfortunately, this is not the case.

A cursory reflection over these changes in EEI of individual sectors illustrated in Figure 5 makes it possible to see the "elephant in the room". The differences in the changes in the values of energy intensity typical of the different economic sectors have to be explained by considering that different economic sectors do express different types of energy end-uses. The differences in economic energy intensity between the industrial and the service sector depend on the nature of the biophysical transformations taking in these two sectors and not by the state of the art of their technology. When considering energy efficiency, the industrial sector and the service sector cannot be compared using the same indicator (Sectoral GDP/primary energy consumption). In biophysical terms these two sectors are "apples" and "oranges". Melting mineral ores in metallurgy or making plastic products in the chemical industry is much more energy intensive than operating computers processing information in the public administration or the insurance sector. These differences in the use of energy input are not reflected in the quantity of added value generated. Therefore, the biophysical performance, or efficiency, or productivity of the technologies used for carrying the various tasks expressed in these two sectors does not map onto a proportional economic performance, efficiency, productivity. For this reason, post-industrial societies with a very large service sector and a large dependency on imports can reduce the operation of their building and manufacturing sector, managing in this way to reduce their energy intensity. But if this is true, then this reduction does not depend on "better technologies" but on a different strategy for generating added value. Now they are generating added value carrying out economic activities not requiring large investment of energy carriers for their end uses (Giampietro et al. 2012). Developed countries tend to externalize the production of energy intensive goods to other countries (Alcantara and Roca, 1995; Proops, 1988).

Should we define this process of de-industrialization and externalization of the most energy intensive economic activities as an increase in energy efficiency of the economy? Is the performance of the economy increased by the elimination of the industrial sector? We have to recall here the wisdom of Carnot. Paraphrasing his statement about efficiency and tailoring it to the analysis of the efficiency of an economy we can say: "*We should not expect ever to get the maximum efficiency possible. The attempts made to attain this result would be far more harmful than useful if they caused other important considerations to be neglected. The economic **efficiency** is only one of the conditions to* *be fulfilled. In many cases it is only secondary.* An assessment of the performance of the economy should include many more criteria than just energy efficiency such as job creation, avoiding externalization of socio-economic and environmental impact to less developed countries.

Looking again at the Document of Guidance for National Energy Efficient Action Plans (NEEAPs) we find a recommendation for measuring primary energy demand and final energy end-use and for establishing targets about: (i) reduction of primary energy consumption; (ii) reduction of final energy consumption; (iii) primary energy saving; and (iv) final energy saving. Again, we are dealing with the problem discussed earlier (in relation to the example discussed in Figure 2) about the weakness of the target chosen in the European Energy Directive based on reduction of inputs:

> *how to know if the reductions and the saving taking place in the energy inputs within the economy are not affecting its performance*?

That is, what are the factors that have to be considered together with the reduction of energy inputs to check whether the implementation of energy efficiency policies is affecting/reducing the performance of the economy? In fact, one could reduce consumption by: (i) reducing existing activities aimed at controlling environmental impact, then this reduction will have an impact on the environment; (ii) reducing the use of machinery increasing labor productivity, then this reduction may have a negative impact on the wage that can be paid to the worker. Again, we are in the same situation in which considering only changes in the consumption of energy does not necessarily provide a satisfactory analysis of the resulting changes in the performance of the economy.

Moreover, crispy quantitative assessments of: (i) the reduction of primary energy consumption; (ii) the reduction of final energy consumption; (iii) the primary energy saving; and (iv) the final energy saving; are simply not possible. When dealing with energetics any quantification of this type is quite complex and the resulting quantitative assessments are difficult to sum into simple tables. This point will be discussed more in detail later on in Section 1.3.

To make things more complex a new phenomenon took place in the globalized post-industrial world. In the last decade the world economy experiences a huge expansion of the financial sector based on the boosting of credit. This expansion has been determined by an explosion of "virtual money" massively pumped into modern economies. This creation of virtual money coming out from "the sky" represents an additional factor of reduction of the energy intensity of the economy. According to the latest report of McKinsey Global Institute of 2015, the global debt has increased since 2007 of **57 trillions** US$, while the debt-to-GDP ratio has not decreased for any major economy over the same period: **debt growth is outpacing the GDP growth** and rich countries are those making the vast majority of this debt. Put it in another way, in the last decade, the world economic growth has been powered by "virtual money" and not by the bio-economic activities of the economy!

http://www.mckinsey.com/insights/economic_studies/debt_and_not_much_deleveraging

By adopting the method of analysis suggested in the Template for the National Energy Efficiency Action Plans we will assess as a successful strategy for getting energy efficiency any massive injection of "virtual money". In fact, the quantity of energy used to increase 1 billion € the GDP of EU with quantitative easing – i.e. the share of electricity used by the computers of the financial sector to add digits to various bank accounts - would result completely negligible when compared with the energy that would be required by the industrial sector to increase 1 billion € its sectoral GDP. This is another reason to conclude that a simplistic mixing of biophysical variables and economic variables is not an effective strategy to build effective indicators of efficiency to be used for policy. According to the EEI indicator IF the EU prints money for covering its current expenses, ***importing rather than producing the most energy intensive goods it consumes***, THEN such a policy would be considered as very "efficient" in terms of EEI. A posteriori this policy may be termed "smart" or a "Ponzi scheme", depending on whether the debt will be repaid and when. In any case it is problematic to consider such a policy as "efficient", by default, especially if this term is associated with a positive normative value.

1.2.3 Because of the openness of the economy and the different levels of credit leverage it is difficult to assess the energy efficiency of individual economic sectors

Abandoning the idea that it is practical to study the relation between money flows and energy efficiency at the level of the whole economy, we can move to a lower hierarchical level of analysis – the one of individual economic sector - to study "energy efficiency" by adopting a view based on bio-physical variables describing biophysical processes.

Then in order to study differences in energy efficiency we have to identify instructive differences in the pattern of energy use across different economic compartments. Let's start this analysis looking at a comparison of the EEI of different economic sector in EU given in Figure 6. In the figure we can see three outliers in the values of Economic Energy Intensity of the Productive Sector: (i) Ireland has a very high production of added value per hour of work with a relative low level of energy consumption; and (ii) Finland and Sweden with a very high level of energy consumption per hour of labor in the productive sector.

As discussed by Giampietro et al (2012) the "miracle" in energy efficiency of Ireland can be explained not by the adoption of a "miracle technology" but rather by an accounting artefact: for fiscal reasons money flows associated with the production of some industrial products are accounted in the Irish economy, even if they refer to the biophysical production of goods done elsewhere; (ii) the other two outliers - Finland and Sweden – represent a different case. The industrial sectors of these two countries are using much more energy per hour of labor than the other industrial sectors of Europe. The question to be answered in relation to an analysis of efficiency and technological performance is the following one: why they are using so much energy?

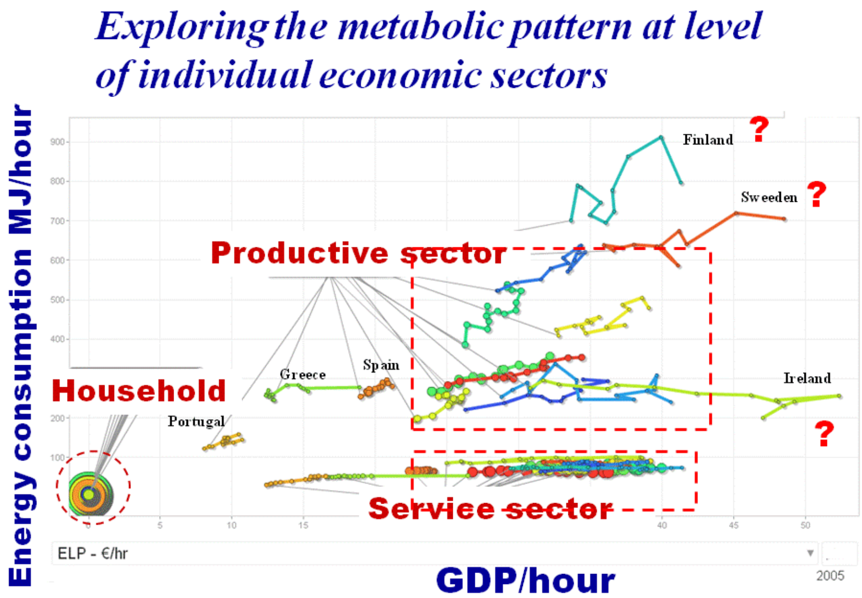


Figure 6 – Overview of different characteristics determining the EEI of economic sectors of EU countries in the time window 1990-2005 (Giampietro et al. 2012)

Is this higher energy consumption of the industrial sectors of Finland and Sweden determined by the adoption of inefficient technologies? Rather the difference can be explained by the fact that their industrial sectors are based on a mix of activities not found in the other countries? In order to answer this type of question one has to open again the black-box of the "building and manufacturing sector" and try to explain the differences in the characteristics of the industrial sector of Finland and Sweden, compared with the other industrial sectors in EU. This movement to a lower level of analysis requires considering the characteristics of the sub-sectors making up the building and manufacturing sector. If we look at the functioning of the lower level compartment we discover that one of the reasons explaining the high energy use per hour of labor in the industrial sectors of the two Nordic countries is represented by the massive production of forest biomass that is converted into paper pulp. There are also other intensive sub-sectors such as mining that contribute to the intensity. The Paper and Pulp sub-sector reaches levels of thousands of MJ of energy per hour of labor. For this reason, in order to compare apples with apples and oranges with oranges an effective analysis of energy use in different economies should be based on the comparison of data referring to the same typology of sub-sectors. An example of this comparison at the level of the subsector is provided in Figure 7.

Compared with the average values of the in Europe

Paper, Pulp & Print, Year 2010

	EMR_{el}	EMR_{ph}	EMR_{f}
Italy	0,6	0,4	0,5
Spain	0,3	0,5	1,5
Sweeden	4,5	4,9	6,2
Finland	5,8	7,1	2,8
UK	0,5	0,2	0,2
Germany	0,8	0,8	0,4
Hungary	0,2	0,2	0,1
Norway	4,2	1,7	9,1
Bulgaria	0,2	0,5	0,5

much higher than the average

Figure 7 The profile of energy carriers per hour of labor in the Paper, Pulp and Print subsector based on the use of intensive variables – different types of energy carriers (J of electricity, process heat, fuels) per hour of labor, normalized over a set of EU countries (Velasco-Fernández and Giampietro, 2015)

Finland has a consumption of energy carriers per hour of labor that is 5 - 6 times the EU average, whereas Italy has a consumption of energy carriers per hour of labor that is less than half the EU average (a detailed comparison of the characteristics of the industrial sectors of EU will be provided in the Deliverable 4.2). The quantitative comparison illustrated in Figure 7 is important because it illustrates two key points:

(i) by moving to lower levels of analysis we can finally address the technical aspects of the "end uses" associated with specific economic activities. Then it becomes possible to study the factors determining the difference of energy performance across different countries in terms of specific processes of production and associated technologies;

(ii) when moving across different scales of analysis we have to adopt non-equivalent accounting of energy quantities. In fact, the quantitative assessments given in Figure 6 are based on data for the consumption of energy referring to the category of accounting of Gross Energy Requirement (the details of this accounting are given in Section 1.3). In this strategy of accounting, Joules of electricity and Joules of thermal energy have been aggregated in a single quantity – Joules of Tons of Oil Equivalent. As discussed below, this choice of accounting makes it possible to use a single number for the assessment (a PRO), but it implies losing information about the relative importance of electricity and thermal energy in relation to the specific set of end uses (a CON). When moving our analysis to a lower hierarchical level (Figure 7) the characteristics of the technical coefficients describing functional biophysical processes do matter. For this reason, at a lower level we have to use a characterization describing the profile of use of energy carriers in terms of data arrays capable of keeping separated the accounting of quantities of electricity and the quantities of fuels. As discussed below, there are activities that can only be carried out using electricity and other only using fuels. The characterization provided in Figure 7 is capable of specifying the expected profile of different quantities of energy carriers – electricity, process heat, and fuels (in this case per hour of labor) – that should be associated with the expression of a specific economic activity. In order to take in consideration the specific characteristics of biophysical processes it is essential to be able to associate the profiles of energy carriers with the specific profile of end uses required in the sub-sector. Only at this hierarchical level of analysis and after having organized the data of energy consumption in arrays it becomes possible to study the differences in the rate of use of production factors (labor, electricity, fuels, process heat) for expressing specific tasks.

When analyzing the performance of Finland and Italy in this way – Figure 7 - we can detect clear differences among the sub-sectors of the industrial sector. These should be the relevant piece of information to define policies aimed at improving the "productivity", "efficiency" and "competitiveness" of the economy. However, the data presented in Figure 7 still do not refer to technical coefficients of specific biophysical processes. According to Figure 7 the energy intensity of Sweden and Norway is much higher than the energy intensity in Spain or Italy. This difference simply reflects the fact that the pulp and paper sector of the Nordic countries is carrying out a set of activities - producing a massive amount of pulp cutting trees from the forest and making paper out of it (they are major exporters) – which are not carried out in the pulp and paper sectors of other EU countries. The pulp and paper sub-sectors in Italy and Spain just recycle paper in much smaller volumes (they are net importers). These differences simply tell us that the statistical offices are not providing useful information for studying the efficiency of this sector, when comparing different countries. They are including in the same category of accounting data referring to economic activities that are different. That is, data used to generate Figure 7 are taken from statistics grouping in the same category (using the same label) economic activities that are quite different across EU 28. Using given statistical data, we cannot make any inference about the "productivity", "efficiency" and "competitiveness" of the technologies used in the pulp and paper industry of EU countries. Looking at the table in Figure 7 we can clearly see that the data arrays describing the relations over energy flows in pulp and paper sectors of EU are totally different from each other. When statistical offices are grouping, in the same category of accounting, data referring to apples and oranges the information they provide does not allow a meaningful comparison. Obviously, the same problem is found across all the sub-sectors of the industrial sector – some processes produce metals by recycling scrap metal other by melting minerals. The relative difference in energy intensity has nothing to do with the efficiency of the technology used! This problem will be considered in detail in the second Deliverable (4.2) of Work Package 4.

An additional problem indicated by the example of paper and pulp paper is represented by the level of externalization provided by imports. As discussed earlier, in Europe (and in other developed countries) the industrial activities that are more energy intensive (e.g. the heavy metallurgy) tend to be externalized to other countries.

1.2.4 Implications of these three points on the analysis of energy efficiency

The lesson to be learned from these examples is that in order to make it possible a comparison of the "energetic performance" of the various sectors and sub-sector of the EU economy statistical offices should:

(i) define new taxonomies of sub-sectors provided trying to identify and group the activities carried out in each category in a way that makes it possible to explain the data with the specific characteristics of technical benchmarks. Differences in energy intensity across sub-sectors should be explained by differences in the biophysical characteristics of the various processes;

(ii) define the level of openness of the sectors and sub-sectors considered. This would require to associate to data about consumption of energy also data about the level of imports and exports of the various sectors considered. IF the fraction of the domestic consumption covered by the domestic supply provided by a given sector is small – e.g. if only 10% of domestic consumption is covered – THEN we are dealing with a function that the country has externalized to other economies. In this case, the assessment of energy efficiency of the sector is not particularly relevant for assessing the "productivity", "efficiency" and "competitiveness" of the technologies used there. IF the sub-sector of a country is producing much more than it is consumed by the country THEN the economy is exporting because of comparative advantages. In this case, an analysis of the technical coefficients and the performance of the sector is very useful, since it can be used to define benchmarks for the performance of the specific economic activity (the profile of end use described by the data array). It should be noted that many of the required data are already available to the statistical offices. The problem at the moment is generated by a lack of coordination in the definition of categories of accounting, when coming to different typologies of statistics (energy, labor, material imports and exports) across the division in sectors and subsectors.

Again, if we look at the method of analysis suggested in the Template for the National Energy Efficiency Action Plans, in relation to the Guidance (39) for the measuring of energy saving in the industry we find the following suggestion:

"The EED requires the Member State to declare savings achieved through measures and to explain how the savings figures were determined. Achieved and forecast savings for the industry sector may be presented here. The Template is structured in such a way that savings may be described separately for each sector. Alternatively, Member State may choose to describe the savings in more detail in relation to specific measures/groups of measures addressing the industry sector or by including more detailed on industry-related energy savings under sections 2.3 and 2.4 or in a separate annex to the NEEAP."

According to what discussed do far, in relation to the analysis given in Figure 7, it is not clear: (i) how to measure the expected savings? The template asks for just a single quantitative measurement of "energy use" – the quantity of just an input;

(ii) against what type of output changes in the input should be considered? Output measured in what?

(iii) when comparing sectors of the EU using the labels used by the statistics are these data referring to the same "sector" or rather – as done when studying and comparing the pulp and paper sector - are we describing energy flowing through "apples" and "oranges"?

(iv) how to deal with the fact that the industrial subsectors within the EU28 do have different levels of externalization of some of their internal phases to other countries?

(v) why a reduction of energy consumption in a given subsector (which does not even map onto a set of homogeneous biophysical activities), which is operating at an unknown level of externalization, should be considered as an indicator of an increase in energy efficiency?

We claim that, at the moment, using the actual system of statistics about energy consumption in the industrial sector **it is not possible to make any inference about the performance in the use of energy in any of the sub-sectors of the industrial sector, let alone for the whole industrial sector**. Obviously, this implies also that it is impossible to compare their performance within the EU28.

1.3 Dealing with the fact that "not all joules are the same"

The content of the text of this section is quite technical. On the other hand, if one wants to get into the business of accounting energy quantities and describing energy transformations it is essential to be aware of some basic scientific facts and rules to be followed when doing it.

1.3.1 Categories of accounting in energetics

Let's start from some basic principles of Energetics helping to understand the epistemological challenge implied by energy accounting. In fact, not only are there different forms of energy – e.g. thermal energy vs mechanical energy - but also there is a systemic ambiguity on how to aggregate quantities referring to different energy forms across different scales, processes and narratives (Giampietro and Sorman, 2012). The energy analysis of complex socio-economic systems must take into account not only the issue of scale (what has been illustrated in Section 1) – the analysis of the Economic Energy Intensity of the whole economy, individual economic sectors and individual sub-sectors is different depending on the chosen scale - but also consider that it is important to maintain the semantic distinction between non-equivalent energy forms: (i) energy forms are of different physical nature (mechanical, thermal, chemical); and (ii) energy forms do play a different role within the metabolic pattern of the society: Primary Energy Sources (PES) are energy forms outside human control; whereas Energy Carriers (EC) are energy forms under human control. Finally, End Uses (EU) of Energy carriers refers to the expected characteristics of known processes associated with economic activities. In order to have a specific End Use we must have a specific "processor" – that is a specific profile of inputs - human activity, power capacity, electricity, fuel and process heat – that have to be applied in a coordinated way to guarantee the proper expression of a given task (for further reading: Giampietro et al. 2012, Giampietro and Sorman, 2012; Sorman and Giampietro, 2012).

Only after distinguishing between these relevant categories of energy forms it becomes possible to establish a link between: (i) the production patterns of energy carriers from available natural resources (either locally produced or imported/exported); and (ii) the consumption patterns of energy carriers associated with the set of end uses that expressed by society.

Primary Energy Sources (PES) – ***energy forms outside human control (they must be available, they cannot be produced)***. These energy forms refer to the input required by the energy sector to generate the supply of energy carriers used by societies. According to the laws of thermodynamics Primary Energy Sources (PES) cannot be produced and must be readily found in nature. Therefore, since PES are found in their original biophysical form such as below-ground fossil energy reserves (coal, gas, oil), blowing wind, falling water, sun, and biomass; they should also be expressed in biophysical quantities such as tons of Coal, tons of falling water for hydro, kg of uranium.

The information about the availability of PES is essential to know the severity of external constraints associated with thermodynamic limit to the process of energy transformations. The gross requirement of PES indicates the quantity and quality of favorable gradients which must be available to a society, in order to be able to produce an adequate supply of energy carriers. When considering quantities of PES based on chemical energy, such as fossil energy, it is possible to calculate an energetic equivalent (which is assessed using the calorific value of the fossil energy). In alternative other type of primary energy sources, such as wind and hydro, provide a supply of mechanical energy as an external input provided by natural processes outside human control.

Energy Carriers (EC) – (secondary energy) - – ***energy forms under human control (they must be produced and this implies a requirement of production factors).*** Energy carriers are produced by the Energy Sector of a society by exploiting available Primary Energy Sources and by investing production factors (labor, power capacity and inputs of energy carriers). This category refers to forms of energy that are required by the various sectors of a society to perform their functions. Examples of energy carriers include liquid fuel burned in a furnace, gasoline in a car or electricity used in a factory. An energy carrier, therefore entails an energy cost for its production (1 MJ of energy carriers for its production requires a larger amount of "energy" in terms of MJ supplied by the PES). The distinction between "Energy Carriers" and "Primary Energy Sources" is extremely important since these two labels refer to energy forms of different quality. It is crucial to note that, like for the summing of different monetary flows (1 US$ cannot summed to 1 Japanese Yen as such), it is NOT possible to sum 1 kWh of electricity (which is an energy carrier of mechanical energy) to 3.6 MJ of crude oil (a Primary Energy Source of chemical energy transformable into thermal energy).

Energy end-uses (EU) – This expression refers to the conversion of energy carriers into useful tasks/works requiring the availability of an appropriate processor (a combination of labor, technology and other inputs). These conversions take place in the various sectors of society such as agriculture, industry, and services. The definition of "end uses" is important because it defines specific profiles of requirements of a mix of production factors (labor, power capacity and a mix of energy carriers of different type) that must be combined in order to be able to express the different tasks required to reproduce and maintain a society. The concept of processor has been introduced in relational analysis (Louie, 2009) whereas the same concept has been introduced as "extended production function" in bioeconomics (Mayumi, 2001; Ayers and Warr, 2005). For this reason, end-uses can be labelled using the name given to the specific functions expressed in different economic activities such as "melting iron" in the industrial sector or "lighting" in the residential sector.

1.3.2 The problematic handling of the differences in energy quality in energy accounting

The question "Would you rather have 100 MJ of electricity at your electricity socket outlet OR 100 MJ of hot bathwater in your bathroom?" cannot be answered without a proper framing. In fact, for a person living in New York City this question proposes a dilemma between "checking her e-mail" versus "taking a shower". However, when cultural factors are in play limiting the option space of usable energy forms – e.g. for an Amish belonging to a culture that refuses to use electricity - this dilemma would not even be a relevant one. Whether electricity is a form of energy depends on the culture of a society. This is to say, that since "all joules are not equal" (humans eat pizza, whereas cars eat gasoline) it is extremely important to be able to couple the right category of accounting of energy forms with the right end user of the input of energy carriers. Uranium is produced in Namibia but is exported from there as a mineral (no relation to energy). On the contrary uranium is imported in France and used there as a Primary Energy Source. Whether uranium is a Primary Energy Source or a mineral depends on the capability of the users.

Within the energy sector different quantities of energy required for different transformations continuously change their form through metabolic pathways. PES become EC and EC can change their nature (from thermal to mechanical). The discussion we had so far can be wrapped up using the scheme given in Figure 8.

Specific end uses can accept only certain energy forms and not others – e.g. refrigerators do not run on gasoline and airliners do not fly on electricity. When dealing with specific "energy services" such as – transportation, air conditioning, illumination, etc. – it is possible to refer to "unitary operations" characterizing the specific energy service considered – e.g. energy per ton km transported, or CO_2 emissions per km passenger, etc. However, also in this case, it is easy to incur into errors when trying to generalize or scaling the characterization to another level of analysis. The complexity associated with the concept of metabolic pattern of modern societies requires considering four basic non-equivalent categories of accounting for energy forms.

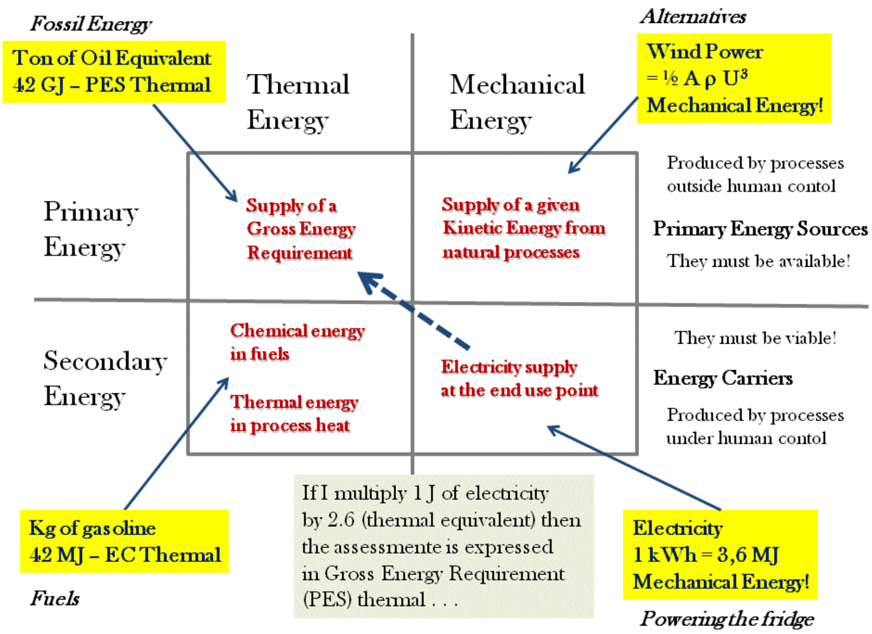


Figure 8 Different categories of accounting required to deal with the fact that different energy forms cannot be summed

There are two important distinctions, illustrated in Figure 8, to be considered in the accounting of quantities of energy:

1) *the distinction between* ***Primary*** *energy and* ***Secondary*** *energy*;

2) *the distinction between* ***Mechanical energy*** *– i.e. kinetic energy, electricity on one hand- and* ***Thermal energy*** *– i.e. chemical energy, heat on the other hand*.

Classic thermodynamics was exactly developed for dealing with the fact, that 1 joule of mechanical energy has a different quality from 1 joule of thermal energy! These two criteria of distinctions are crucial for those that want to calculate indices assessing the performance of energy conversions. In fact, no serious economic accountant would sum 1,000 € of profit to 1,000 € of gross revenue, only because these two quantities are both measured in the same unit: €. In the same way, when handling quantities of energy, even if some quantities are expressed in the same unit – Joule – if the Joules belong to different categories of accounting then they cannot be summed. It is important to be aware that some quantities of energy ("more useful energy forms" should be considered in energetics as "profit" in economics) can be obtained only using a larger quantity of energy ("primary energy sources" should be considered in energetics as "gross revenue" in economics). Therefore, it is essential to look at the whole set of transformations of energy, to understand the role that different categories of energy forms play in the whole metabolic pattern. For example, we can say that "the electric car" is reducing the CO_2 emissions of transportation. But this statement is true only when considering the conversion of kWh of electricity (an energy carrier of mechanical energy used as input to the car electric engine) into passenger miles. This assessment refers only to the conversion EC → End Use. Depending on the Primary Energy Source used to produce the electricity – e.g. by using coal in a low efficiency power plant – the "end use" of the electric car can emit more GHG gases than a conventional car fueled with methane. The overall assessment requires considering the two consecutive conversions: PES → EC → End Use.

This example shows that generic indicators of performance referring to conversions analyzed one at the time, at the local scale, and then used out of context are dangerous. Assessments should always be done by considering the implications of two consecutive transformations and relative "efficiency" taking place in the society:

(i) Primary Energy Sources (PES) →Energy Carriers (EC) - in the energy sector – this efficiency depends on: the technologies used in the conversions and the mix of the PES used for the production (depending on the mix of EC used in the end uses);

(ii) Energy Carriers (EC) → End Uses (EU) - taking place in the rest of the society, at the local scale, where the EC are converted in energy services. This efficiency depends on the technologies used for the conversion and the wisdom of those using the technologies.

In conclusion, in order to generate an integrated analysis of these two different types of efficiencies – Efficiency 1: PES → EC and Efficiency 2. EC → End Use - and to study their relation within the energy sector it is necessary to have quantitative information organized on categories referring to the different forms of energy: (i) Primary Energy Sources - renewable and non-renewable, imported or locally available; and (ii) Energy Carriers – gross requirement, losses, required to generate energy carriers, available for the end uses in the society. An analysis of the metabolic pattern of a society should be done by integrating the quantitative analysis based on the accounting of different energy forms and also other physical quantities – an example of the categorization of quantities of energy forms in the energetic metabolic pattern of Spain (2004) is given in Figure 9.

However, this analysis requires a new way of organizing the accounting of energy flows something different from what done at the moment by energy statistics (this point is addressed in section 2).

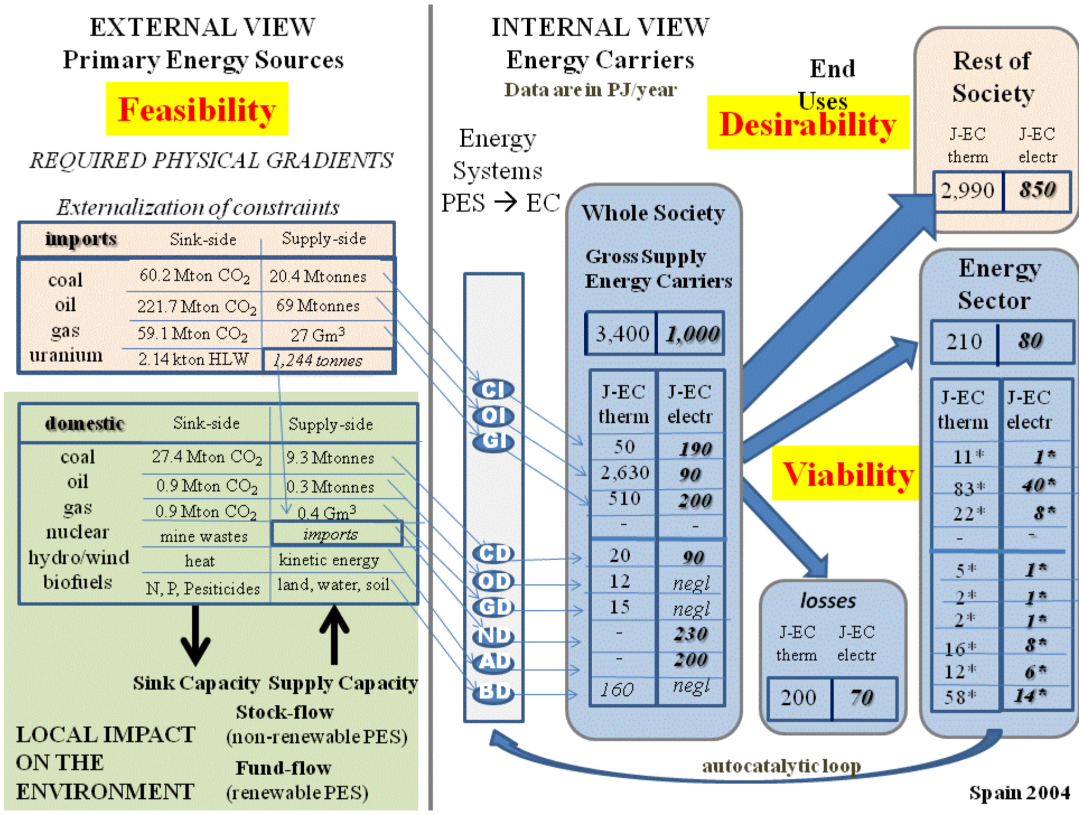


Figure 9 Energy flows through Spain based on categories of accounting providing different types of relevant information (Giampietro et al. 2013)

1.3.3 How statistical offices handle the “mission impossible” of aggregating the accounting of different energy forms in just a metric (but in this way they destroy information)

In general terms, the quality of electricity is considered higher than the quality of thermal energy because of its superiority to do work. This perception reflects the history of thermodynamics: classic thermodynamics was developed in order to convert thermal energy into mechanical energy. As a matter of fact, the very concept of efficiency was developed by Carnot and the other pioneers of the field to improve the performance of this conversion. Moreover, it is much easier to transport electricity for long distances and, as energy carrier, electricity is much more flexible than thermal energy in a multitude of uses. For this reason, electricity has been proposed as a form of mechanical energy in exergy accounting (e.g. by Ayres). However, this difference in quality among energy carriers generates a problem in the accounting of quantities of energy in modern energy statistics. Unless the quantities of energy carriers are kept separated (1 kWh electricity = 3.6 MJ of mechanical energy; and 1 MJ of fossil energy = 1 MJ of thermal energy) every aggregation of these two values implies a loss of information about the characteristics of the end use associated with their consumption: 1 MJ of electricity ≠ 1 MJ of thermal energy! In fact, when aggregating the two types of energy inputs we lose information about the relative mix of electricity and other fuels in the overall consumption of an economy. On the other hand, if we do not handle this difference we end up with a bifurcation in the assessment of energy consumption in a society.

As illustrated in Figure 10, when measuring electricity consumption in kWh (actual Joules of electricity), measuring the consumption in terms of secondary energy, we obtain that electricity represented the 18% of the total final energy consumption in Spain in 2007. On the other hand, if we measure the primary consumption in Tons of Oil Equivalent (Gross Energy Requirement thermal) we obtain that electricity represented 36% of the total consumption of Spain in 2007. The first quantitative information has to be used to assess the effect of changes in efficiency in electric appliances. Better electric appliance will reduce the consumption of electricity measured in secondary Joules (e.g. 156 10^9 kWh). Whereas when looking at the total primary consumption going into the production of electricity – 40 M TOE – we are looking at information related to the requirement of power plant capacity or to the requirement of PES to be imported by the country. It should be noted that a change in the relation between the consumption of PES and the consumption of secondary energy can be obtained without any change in technological performance, but just by changing the mix of PES used in the production of electricity. For example, in a given year, this can be obtained by dramatically increasing the hydroelectric production (even though this will require taking out water from reservoirs). Yet this statement is true only if we adopt the method of energy accounting of Eurostat! [the explanation of this point is given below].

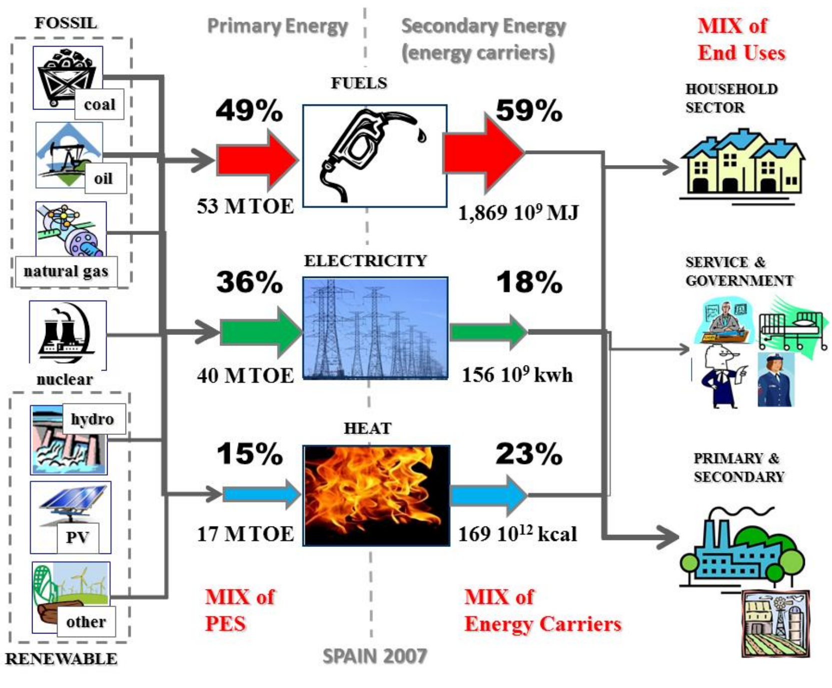


Figure 10 The bifurcation in the accounting of electricity consumption when considering simultaneously assessments assessed in Joules of primary and secondary energy

Different mixes of different carries may perform ***better*** and/or may be requires for ***different tasks***. For example, in modern economies 100 Joules of electricity do more economic work than 100 Joules of sunlight (Hall et al., 1992). In the same way 100 Joules of petroleum can do more economic work than 100 Joules of coal (Adams and Miovic, 1968; Cleveland 1992; Cleveland et al., 1984). For this reason, there is no uniform method for defining a quality criterion capable of ranking the utility of energy carriers in a substantive way. As in the example of the fridge using electricity and airliner using kerosene different end uses, associated to specific tasks define what should be considered as an "admissible" input of energy carriers (Cottrell, 1955; Smil, 2003). This implies that we should find expected patterns in the mix of EC associated with economic activities – e.g. the transport sector has a larger consumption of MJ of fuels (thermal energy), the banking sector has a larger consumption of electricity.

This heterogeneity of categories required in the accounting represents a major problem for energy statistics that by tradition have been trying to simplify the assessment of energy flows using a simple (linear) representation of energy transformation and a single metric. Energy statistics try to maintain the distinction between Primary (PES) and Secondary (EC) energy but then they had to get rid of the distinction between mechanical (electricity) and thermal energy (fuel and process heat). To achieve this result, in the statistical accounting, quantities of energy belonging to these two different categories are aggregated into a single category. This category could be *toe* (tonnes of oil equivalent – equal to 42GJ of thermal energy), *tce* (tonnes of carbon equivalent – less frequently used nowadays) that is a category referring to Primary energy equivalent – or in alternative *Joules of energy commodities* an accounting category not referring to any specific type of energy form of those included in Figure 8 (see Giampietro and Sorman, 2012; Giampietro et al. 2013). However, in both cases the protocol adopted to achieve this result remains problematic.

As noted earlier the flow of 1 Joule of energy carrier entails an energetic expense of more than 1 Joule of primary energy sources (energy carriers are under human control and therefore they imply an "energy cost" for their production and handling). On the contrary, Joules of PES are gift of nature (the cost for humans is only felt when PES are exploited and transformed into EC). At the same time as discussed earlier 1 J of electricity – an energy carrier - tends to be more useful (as a form of mechanical energy) for many end uses in modern societies than 1 J of energy carrier providing thermal energy – e.g. a fuel. Then how it is possible to generate a system of accounting based on a single metric?

Though the statement might seem surprising, statistical offices bear important responsibility for sloppy accounting – something not unknown to the most responsible among official statisticians. In fact, they tend to provide general overviews of the energy use in modern society - including quantities of PES and EC belonging to both categories (mechanical and thermal) based on a single category of accounting. In order to obtain this result, they have to get rid of the conceptual differences indicated in Figure 8. The worst part is that they do so by adopting two different solutions:

1. *Opportunity Cost Method or the Partial Substitution Method* – adopted by the BP and American statistics. According to this method, everything is measured in Gross Energy Requirement thermal equivalent (e.g. Tons of Oil Equivalent – primary energy equivalent). That is, the primary energy equivalent of hydroelectricity and nuclear electricity (and any other electricity generated not using fossil energy sources) is accounted considering an amount equivalent of primary energy, which would be needed to obtain them if fossil fuels were used as PES. To calculate this amount equivalent, one has to define a conversion factor Joules of fossil energy/Joules of electricity (the efficiency of the power plant powered with fossil energy). For this calculation the factor used refers to the average efficiency achieved in OECD

countries: 38.5%. This value translates into a conversion factor: 1MWh = 0.086toe/0.385 (1 J of electricity has a thermal energy equivalent of 2.6 J). With this solution all the quantities of thermal energy EC is accounted considering the PES needed to produce the EC and all the EC of electricity is accounted as if it were produced using fossil energy as PES. The obvious negative aspect of this method is that it introduces "virtual flows of energy" which are not taking place in the reality. For example, the virtual tons of oil equivalent assessed for a hydroelectric plant do not map onto the relative amount of CO_2 emissions, moreover, countries with a large hydroelectricity production result as consuming large quantities of PES, which they are actually not consuming.

2. *Physical Energy Content Method* - used by IEA and Eurostat. This method adopts an inexplicable accounting protocol mixing and summing different categories of energy using a variety of conversion factors. In practical terms the electricity produced by Nuclear plants is valued on the basis of the heat coming from the nuclear reactor (1MWh = 0.086toe/0.33) – a conversion of 3 J thermal per 1 J of electricity. However, when dealing with hydroelectricity the energy content of the electricity is converted directly to primary energy without using a conversions factor: 1MWh = 0.086 toe – the J of electricity are counted as such because they have been produced using mechanical energy (without inputs of thermal energy). In this way they are summing 1 MJ of mechanical energy (the electricity produced by hydropower) to 1 MJ of thermal energy (in a fuel) with no conversion factor: 1 MJ of electricity + 1 MJ of fuel = 2 MJ of energy commodity. IEA and Eurostat have switched from the partial substitution method to the physical energy content method claiming that "virtual values" produced from hydro had no real significance.

However, this bifurcation in the methods of accounting energy quantities in statistics generates problems. As illustrated in Figure 11 if we compare the statistical data describing the energy mix of Sweden in 2005, we can see that in spite of the fact that in Sweden the electricity produced by hydroelectric plants is more than the electricity produced by nuclear plants, when adopting the physical energy content method (used by IEA and Eurostat) the estimates of the supply of electricity of the alternative sources result to be 1/3 than that of nuclear energy! The system of accounting adopted by EUROSTAT gives an extra importance to the thermal energy of nuclear plants and underestimates the importance of alternative energies. In fact, 1 J of electricity produced by a nuclear plant is accounted as 3 J (of energy commodity), whereas 1 J of electricity produced by a hydroelectric plant is accounted as 1 J (of energy commodity).

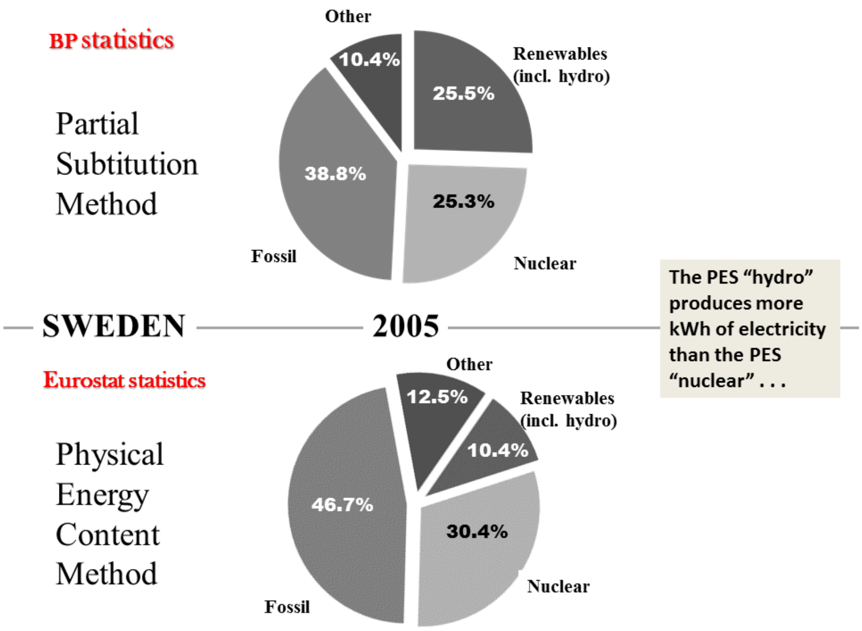


Figure 11 Differences in the assessment of the energetic metabolism of Sweden (2005) according to two "schools" of energy accounting (Giampietro et al. 2013)

Yet it should be noted that the different conversions of PES into EC specific for different energy systems – nuclear, hydro, coal, wind - do not have anything to do with the concept of efficiency as a measure of technological performance. In fact, in order to measure the performance of the production of electricity in relation to a given technology (the technical coefficients in the various processes taking place in a production system) we should compare the technical coefficients of: (i) hydroelectric plants with hydroelectric plants having similar characteristics; (ii) nuclear plant with similar characteristics; (iii) coal plant with nuclear plants having similar characteristics; and so on.

1.3.4 The importance of contextualizing energy assessments within the "big picture": the pay-back time of innovation for energy efficiency

Another very popular narrative within the EU discourse is that of eco-design. This concept is applied mainly to the energy use at the household level. Clearly, nobody can deny the importance of achieving more efficient energy uses at the level of the household. However, one has to keep in mind that residential electricity consumption is around the 20% (when considering J of secondary energy and about 40% in GER thermal equivalent) of the total final consumption. Moreover, it refers to types of energy services that are relatively easy to guarantee (low heat, air conditioning, illumination). Focusing on the household sectors allows one to remain conveniently blind to the efficiency of energy use in the economic sectors that consume the remaining energy, in particular the bulk of liquid fuels, in order to provide jobs and keep the economy going. As noted by Heinberg (2016) *"..the other 80 percent of energy usage occurs mostly in transportation, agriculture, industrial processes, and in heating buildings, and currently* *requires liquid, gaseous, and solid hydrocarbon fuels with a big challenge ahead of us in electrifying those areas of energy usage."*[1]

For example, changing lightbulbs into more efficient ones, say converting classical 65Watts bulb into 5Watts LED bulbs, would imply a saving of 60Watts consumed on average of 7 hours per day over the course of the uses of a year (330 days), corresponding to a savings of 140kWh. Assuming, for instance, that every person in Spain converts one light bulb, 45 million (multiplied by 140kWh) would make a saving around 6Twh. This corresponds to only around 2% of all of Spain's electricity consumption, of which in 2016 was 263.1TWh[2]. If we

consider then that the electricity consumption represents around 20% of all J of EC used, we realize that we are talking of an overall effect (reducing of 2% the 20%) which is well below the 1% of the total. This is another example helping to put things into context when talking about the possible achievements obtained through efficiency.

Another popular narrative used to discuss of policies increasing the energy efficiency at the household level is the economic pay-back time of the investment done by the consumers buying more efficient appliances. The pay-back time is the period of time that the consumer has to wait to get back, because of reduced expenses for the electricity they consume, the money invested in buying more efficient appliances. However, less attention is given to the pay-back time of the energy investment done by society in producing the more efficient appliances. In fact, if it is true that energy is saved by more efficient appliances, it is also true that energy is spent in producing these more efficient appliances. We can calculate the saving of electricity given by a new appliance – e.g. a power drill - as follows:

$$\text{Electricity/year} = PC \times \phi/PC \times UF$$

Where:

Electricity/year = the quantity of electricity consumed per year

PC = Power Capacity – the power in kW of a power drill

ϕ/PC = the flow of electricity consumed by the power drill per hour of activity

UF = Utilization Factor of the power drill

Just for the sake of illustration, assuming that a 500 W power driller is used for 3 hours in a year it will consume a quantity of 5.4 MJ of electricity in a year. Let's then assume that a more efficient model of power driller will be introduced on the market making it possible to have a significant increase in efficiency – e.g. a 40% increase. This implies that the same energy service can be generated with less electricity consumption. This increase in efficiency will imply a reduction of the quantity of electricity consumed for this task/end use of 2.2 MJ per year. Assuming that the energy spent for the production, packaging, handling and transportation of the power driller (these are assessments based on LCA) is about 100 MJ (expressed as gross energy requirement thermal), then

[1] http://www.postcarbon.org/lessons-along-the-path-to-100-percent-clean-energy/

[2] http://www.ree.es/sites/default/files/downloadable/preliminary_report_2015_1.pdf

the saving obtained by a significant increase in efficiency (40%!) would imply a biophysical pay back of the order of almost 5 decades! To make things more difficult, if the electricity used by the appliance is produced by renewable energy (having a very CO_2 emissions per kWh supplied), whereas the energy used in the manufacturing and in the transport of the appliance is based on fossil energy (having significant levels of CO_2 per MJ used), we may face a situation in which a constant turnover of electric appliances – generated by policies aimed at a maximum of efficiency improvement - may increase both the consumption of energy and CO_2 emission in relation to the expression of the given task. Obviously, the case of power drillers is an extreme case featuring an appliance with a very low Utilization Factor (hours of use in a year). Other appliances as refrigerators, air conditioners have a much larger utilization factor and with them increases in efficiency have a major impact. In any case, this example should be used as a warning: it is always important to start any assessment of the potentialities of policies dealing with increases in energy efficiency by contextualizing the role that the specific energy conversion (or the specific energy system) plays within the large picture and the embodied energy in the process of replacement. The pay-back to be studied should be not only that of the investment of money of the consumer, but also the energetic pay-back for society associated with the production and use of the power capacity.

1.3.5 The importance of contextualizing energy assessments within the "big picture": Jevons' paradox (in the long term efficiency increases consumption rather than reducing it!)

Jevons' paradox states that an increase in efficiency of resource use may generate in the long term an increase in energy (or resource) consumption rather than a decrease (Polimeni et al. 2008). Therefore, understanding the nature of Jevons' Paradox is extremely important in relation to sustainability because it challenges the conventional wisdom of energy policy based on the goal of improving energy efficiency. Consequently, this hypothesis generated an intense debate in the field of sustainability science and a lot of quantitative studies have been done to prove or to disprove the validity of this paradox. However, those carrying out quantitative analysis aimed at exploring this issue tend to avoid the term "Jevons paradox" focusing rather on the term "rebound effect". The term "rebound effect" is used to avoid addressing the epistemological complications associated with the fact that the system whose efficiency is studied will change its identity because of the innovation.

For this reason, one would expect any discussion of the role of efficiency improvement on sustainability to start by addressing the basic epistemological conundrum inherent in Jevons paradox – the investigated system becomes something "different" after the improvement. That is, when studying the effects of "efficiency improvement" – defined here as a change associated with the way a given process is carried out - it is impossible to generate a quantitative representation that will remain valid over time (before and after the innovation) because a change in the identity of the system tend to change the definition of what should be considered as the performance of the process. This is a standard predicament for the analysis of the evolution of Complex Adaptive Systems. However, as happens with many other complex issues those proposing reductionist quantitative analysis carefully avoids this epistemological conundrum. Perhaps for this reason, economists refuse to adopt the term *Jevons paradox* and prefer to carry out quantitative analyses of this phenomenon under the name of *rebound effect*. The use of a different name reflects the implicit adoption of a hidden epistemological assumption about the applicability of mathematical models: it is possible to represent in quantitative terms changes determined by increases in efficiency by using only a given formal encoding – i.e. a set of variables and a set of equations. Put in another way the narrative of rebound effect assumes that the original selection of variables used to describe *what the system is* and *what the system does* in relation to the chosen definition of performance "before" the change remains valid and useful also "after" the change. This assumption is referred to as *the ceteris paribus hypothesis*. However, an increase in energy efficiency has exactly the effect of changing: (i) *what the system is*; (ii) *what the system does* and (iii) *the definition of performance for a given transformation*. Therefore, the combination of these changes would require an update of the set of proxy variables, parameters and indicators of performance used in the model. Jevons paradox requires acknowledging the implications of a phenomenon of structural and functional change (i.e. emergence of new features) due to evolution. This emergence requires an update of the quantitative representation on the semantic and formal side. Jevons himself states: "*Now, 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 excite a new activity in most other branches***" (Jevons, 1865 - p. 141, italics added).

The first italics part refers to the structural change, and the second part to the functional change. In essence, Jevons' own words imply that we should always expect that a change in efficiency may result in a change in the identity that we assigned earlier to the observed system and that these changes will take place at different scales. This makes it impossible to measure the relative change in performance (before versus after) using a simple analytical model based on the original set of relevant attributes and indicators. When dealing with the analysis of efficiency improvements the "ceteris paribus" assumption is simply not tenable.

Accepting the validity of Jevons Paradox implies accepting that increases in efficiency tend to boost the consumption of resources or, put in another way a voluntary reduction of energy consumption in some activities can often result in involuntary increases in energy consumption in some other activities (Polimeni et al. 2008). For example, more efficient steam engines made it possible to transform the first inefficient pumps - into efficient steam engines powering the industrial revolution all over the world. More efficient internal combustion engines transformed utilitarian cars into Sport Utilities Vehicles with a much larger mass, air conditioning and many other gadgets. In general terms we can say that increases in efficiency provide the option for change by having more resources available for doing more of the same in relation to the same task (rebound effect) or to invest the spared resources in doing something else (Jevons paradox). As explained in Polimeni et al. 2008: "*An improvement of efficiency in the set of technological processes sustaining society (e.g. more efficient cars) can generate two different results.*

(i) benign for humans - when adopting a perception of improvement referring to the inside of the black box, an improvement of efficiency may be used to provide a better material standard of living for humans. In biophysical terms this efficiency improvement means having access to more energy and materials to be used in producing and consuming goods and services;

(ii) benign for ecological systems embedding the socio-economic system – when adopting a perception of improvement referring to the environment of the black box, an improvement in efficiency may be used to reduce the level of natural resource consumption and the level of environmental impact. In biophysical terms this efficiency improvement means reducing the impact on the environment, i.e., the environmental loading, associated with the extraction of resources and dumping of wastes from the economic process".

So improvement in efficiency can be used either to improve the situation of humans or the situation of the environment. That is, more efficient agents can: (i) keep doing the same while consuming less; or (ii) keep consuming the same, while doing something different and better. In real life, the second is often the solution of choice.

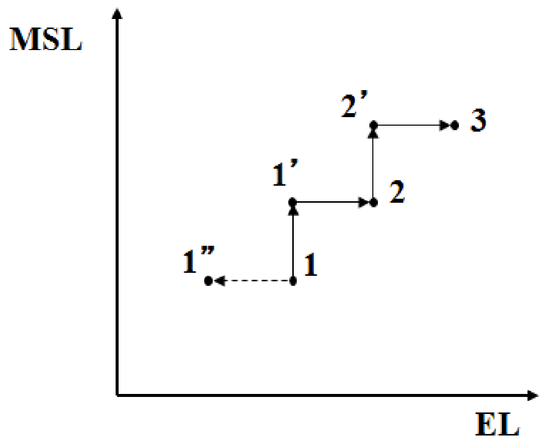


Figure 12 Describing the effect of Jevons Paradox on a plane MSL-EL (after Giampietro and Mayumi, 2008

This fact is illustrated in Figure 12 where the possible effects of an improvement in efficiency are described on a plane: MSL (Material Standard of Living – moving up means improving the situation of humans) and EL (Environmental Loading – moving to the right does improve the situation of ecosystems). Starting from point 1, as the initial situation of the system, an innovation making the agents more efficient makes it possible for the agents to choose. They can move either (1) from point 1 to point 1' – getting a higher Material Standard of Living by keeping the same pressure on the environment (same EL) or (2) from point 1 to point 1'' – using the innovation to reduce the impact on the environment (lower EL), while maintaining the same material standard of living (same MSL).

Because of the innate aspiration of humans for better material standard of living (especially for the children) and the drive for eliminating inequity in any society, it is extremely improbable that innovations increasing efficiency will not be used to improve the conditions of the humans living in a society. Then from Point 1' the society will continue to do “more of the same” expanding in size to arrive to Point 2, where new problems will be solved by a new injection of efficiency. The new solution will provide the option to move back to point 1’ or to move to point 2’. This is where the “silver bullet” will move the society. A detailed explanation of this process based on the analysis of non-equilibrium thermodynamic principles – the tension between minimum entropy principle vs maximum energy flow principle - is available in Giampietro and Mayumi, (2008).

Also in this case, the lesson learned from the existence of the Jevons Paradox is clear. A more robust understanding of the effects of innovations, making possible changes in the energetic metabolism of complex systems can only be obtained by observing the metabolic pattern across different levels of analysis and at different scales. Unfortunately, if we consider changes simultaneously at different scales then, when dealing with metabolic systems, it is unavoidable to face the epistemological conundrum represented by the fact that, as all dissipative systems, metabolic systems are “becoming systems” (Prigogine, 1978). This implies that because of the emergence of new functions, tasks or end uses to be expressed they will sooner or later change their identity and behavior. For this reason, it is very dangerous to assume that a simple indicator – assessing the efficiency of a given process under the *ceteris paribus* conditions – is useful and should be used for informing policies dealing with the issue of sustainability.

1.4 Conclusion: how to handle, with care, the concept of energy efficiency

1.4.1 Wrapping up the points made so far: the pitfalls to be avoided

1. The concept of efficiency is extremely slippery and it should be used with care when building indicators. Unless we are capable of getting the big picture of the whole set of relations over energy transformations taking place in an economy and their consequences in relation to the different functions expressed by the society it is quite dangerous to “optimize” just an operation singled out at a given scale in a given framing.

2. The idea that the theory of classic thermodynamics provides a solid scientific solid back-up for the normative use of the concept of efficiency is a delusion.

3. The mixing of thermodynamic indicators with economic indicators has to be done with extreme care, in order to avoid getting into the blunder of the Economic Energy Intensity indicator applied at the level of the whole country. The relation between energy consumption of an economy and its ability to express a given level of GDP is complex and it requires a careful analysis. A single indicator just cannot handle the resulting complexity.

4. An analysis of the relation between energy and economic variables carried out at the level of the whole society is misleading because at that level energy use and GDP are correlated.

5. The energy intensity of the whole economy is determined by the energy intensities of lower level parts. However, if we want to study this relation we have to learn how to

scale the characteristics of the parts in relation to the characteristics of the whole and the ability of considering the effects of externalizations taking place in the various parts.

6. An analysis of the energy intensity (and therefore of the factors determining the efficiency) of the economy requires analyzing the process simultaneously across different levels of analysis and scales. In turn, this requires the simultaneous use of quantitative analysis based on a combination of different metrics – i.e. a pre-analytical definition of a taxonomy of accounting categories based on different lexicons of variables at different levels.

7. Not all the Joules of energy are equal and not all the Tons of Oil Equivalent emit carbon dioxide so when going at the lower level it is important to be able to track the relations between different quantities of different types of energy forms using categories of energy carriers organized over data arrays.

8. Metabolic systems are open systems: they can externalize the expression of their functions through imports/exports. Considering the effect of imports and exports in determining the performance of the economy would require a different way of compiling statistics. At the moment, we cannot make informed inferences about the performance of the technologies used in the economic process, by looking only at the economic variables describing its GDP.

9. Massive reliance on credit leverage and quantitative easing represent another major source of confusion. Financial operations may boost the GDP without requiring energy uses and relative emissions. If we are not capable of detecting the fraction of the GDP created by biophysical processes (production and consumption of biophysical goods and services) and the part of the GDP created by financial operations (including the massive increase of credit leverage made possible by printing money/quantitative easing), it becomes impossible to assess the effectiveness of policies aimed at increasing sustainability through technical innovation relying only on assessment of GDP at the level of the whole economy.

10. When defining the priority over policies aimed at improving efficiency it is important to start always with the big picture to contextualize the effect of the results. It is better to improve of 2% something that affects 80% of the consumption than improve of 40% something that affects 1% of the consumption. When ranking policies for eco-design the pay-back time has to be calculated not only in economic terms for the consumer, but also in biophysical terms for the producers of new technologies.

11. Last but not least, one has to be aware of the lesson of the Jevons Paradox. Human systems are evolving systems affected by the chronic emergence of true novelties. Human societies will become sooner or later “something else”. For this reason, one cannot trust too much quantitative analysis based on extrapolating into the future the representation of the present situation under the “ceteris paribus” hypothesis. When dealing with the evolution of human systems and innovation one has to expect than any framing of technical issues in terms of a quantitative representation of “efficiency” and “optimization” will create hypocognition (Lakoff, 2010) – i.e. the missing of other relevant aspects. For this reason “wise solutions” should be always preferred over “optimal solutions”.

1.4.2 What are the factors affecting the energy efficiency of EU countries?

We can wrap-up this long discussion of the possible problems faced when trying to use the concept of efficiency in the development of policies with an overview of the five factors to be considered in order to characterize the biophysical performance of modern economies.

The overview provided in Figure 13 clearly shows that any analysis of the biophysical performance of an economy referring to the concept of "energy efficiency" – interpreted as "the achievement of a given result in relation to the use of a given quantity energy input" - must address, in quantitative terms, the role played by the five factors highlighted in Figure 13.

If these implications are not addressed – e.g. when using indicators such as "energy intensity" (GDP/energy input), or "carbon intensity" (CO_2/GDP) - then the quantitative analysis is simply comparing the performance of "apples" with the performance of "oranges" without being able to define: (i) what is the meaning of "performance"; and (ii) what should be considered as an instance of "apple" and what should be considered as an instance of "orange".

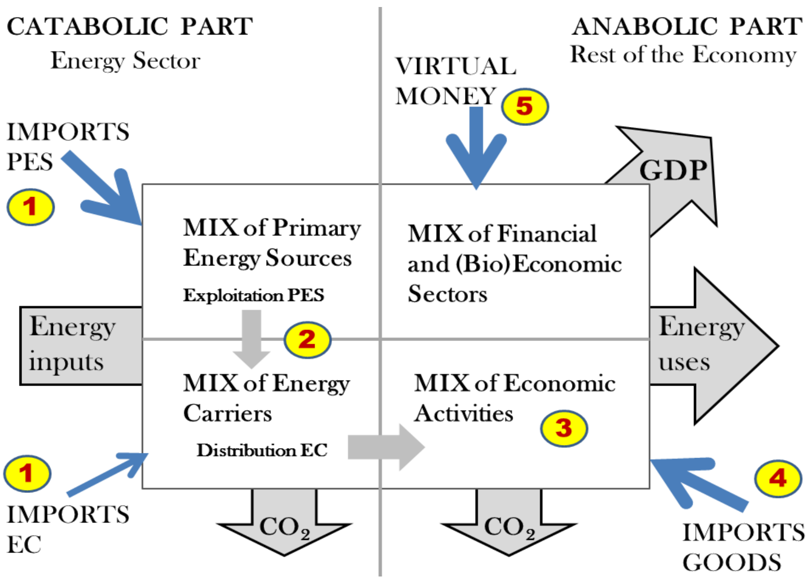


Figure 13 The metabolic pattern of socio-ecological systems and the different factors affecting the value of the energy intensity (and carbon intensity) of an economy

Two of the five factors illustrated in Figure 13 are related to the characteristics of the energy sector:

** Factor #1 – the level of openness of the energy sector*.

A high dependence on imports determines the externalization of requirement of investment of technology, labor, water, land use land and obviously the requirement of reserve of fossil energy (PES). This factor is very important in reducing the consumption of PES and EC in the operation of developed economies;

** Factor #2 – the mix of PES and EC used in the society*.

Obviously, a country capable of producing 90% of its electricity with hydropower will requires less fossil energy and emit less CO_2 (to supply the same amount of electricity) than a country relying on coal power plants. In the same way a consumption of a large fraction of electricity in the mix of EC will require more consumption of PES (if the country does not have access to easy to exploit alternative energy sources). Therefore, differences in the mix of PES and EC will be reflected in differences in the structural elements (technical processes) operating in the energy sector.

These two factors will be explored in quantitative terms in Section 2 of this deliverable looking at the set of energy transformations taking place in the energy sector of EU countries. The remaining three of the five factors illustrated in Figure 13 are related to the characteristics of the rest of the society:

** Factor #3 – the specific mix of economic activities carried out in a society*.

Obviously, the energy intensity of the economy is affected by what is produced in it and how. Also in this case, the mix of biophysical processes carried out in the economy may result more important than the efficiency of the technology used in each of the process. A post-industrial society based on tourism (using old technologies in the tourist sector) will result less energy intensive than an industrial society based on metallurgic production, even if the metallurgic sector is using state-of-the-art technology;

** Factor #4 – the externalization of energy intensive production to other economies*.

The energy intensity of an economy can be also reduced by externalizing the most energy intensive phases of production to other countries. In this case, we can still have an industrial sector made-up of different subsectors, but then we can experience a situation in which many of the subsectors of the industrial sector can reduce their energy intensity by importing raw materials and semi-finished products, externalizing the most energy intensive tasks (or labor intensive tasks!) to other economies.

** Factor #5 – massive policies of credit leverage and quantitative easing*.

The massive creation of virtual money makes it possible to guarantee the welfare state and the expected standard of living by keeping artificially high the GDP. When this solution is adopted, then the governments of post-industrial democracies are forced to buy the consensus of their voters and use a temporary solution (making debt) as if it were a steady state solution. This requires believing firmly that very soon a dramatic economic recovery (a miracle) will make it possible to re-pay the mass of debt that it is quickly accumulating.

The relevance of these three factors will be explored in quantitative terms in Second deliverable of WP 4 – Deliverable 4.2 – providing a quantitative analysis of the metabolic pattern of EU economies across different levels of analysis.

In relation to the Directive on Energy Efficiency 2012/27/EU, it seems that many of the points made in the list of "pitfalls to be avoided" have been missed both in the formulation of the Directive and in the Template circulated for the preparation of National Energy Efficiency Action Plans.

1.4.3 The different story-telling about energy security and energy efficiency

Last, but not least, we believe that it is important to flag the fact that the 5 factors illustrated in Figure 13 are all relevant but they refer to four different story-telling that can be used to provide meaning to the concept of energy efficiency:

1. the geo-political strategic perspective in relation to the definition of energy performance. The level of dependency on PES imports is determined by the quantity of EC domestically produced and by the quantity of EC consumed. Domestic production of EC is determined by two factors: (i) the biophysical cost of production – i.e. the amount of capital, labor and other production factors required for extracting and transforming PES into EC; and (ii) external constraints, because, as noted earlier, human technology cannot make PES. This means that countries that do not have oil reserves cannot extract oil. Using the rationale of MuSIASEM we can define three different strategies for obtaining energy security: (i) relying on a supply of energy carriers obtained with renewable sources (a FUND-FLOW supply in the jargon of flow-fund analysis) available inside the boundary of the socio-economic system: an energy autarchy based on the exploitation of natural processes in a way compatible with embedding ecosystems; (ii) relying on a supply of energy carriers domestically produced by exploiting non-renewable sources – e.g. own reserves of fossil energy (a STOCK-FLOW supply in the jargon of flow-fund analysis); and (iii) relying on a supply of energy carriers obtained by importing non-renewable sources - based on reserves owned by other (importing a STOCK-FLOW supply in the jargon of flow-fund analysis). Solutions (ii) and (iii) should be considered as temporary solutions because of the unavoidable depletion of stocks. Solution (iii) should be considered as "very risky" in the case of supply shortage in the international market. The solution of guaranteeing energy security through imports (the solution adopted at the moment by all developed countries) implies a hidden assumption: that market will be capable forever of guaranteeing such a supply. In turn, this assumption relies on another assumption embodied in modern economic theory. The assumption is that the energy market will always remain in a situation of "moderate scarcity". In fact, according to classic economic theory when the scarcity becomes absolute, the institutions required for trading become first more and more instable and then they tend to collapse. In a situation of absolute scarcity of key resource price mechanism no longer work properly, we should rather expect war. The prolonged bonanza of fossil energy – that have lasted more than half a century so far - seems to have convinced the majority of the people of this generation that "absolute scarcity" of some basic commodity is not supposed to be a possibility in modern societies. However, this belief can be at odd with the laws of thermodynamics. As stated by H.T. Odum "a gallon of gasoline will drive you the same amount of miles, independently of the money you paid for it!"

2. the engineering perspective in relation to the definition of energy performance.

In this narrative the definition of performance is quite narrow: the energy sector has to produce the supply of energy carriers required by society. In this view the demand is given (the demand of society) and given the boundary conditions – i.e. availability of resources – the performance of the process of supply is reflecting the characteristics of the technologies used. When adopting this perspective the analysis tends to be based on the adoption of a local scale – e.g. improving the energy required per mileage of a car or reducing the consumption of electricity used in air conditioning per degrees of reduction in the ambient temperature. At the local scale it becomes much easier to agree on a set of indicators of performance. Yet, as stated by Carnot, we have to use more than a single indicator for characterizing the performance of a process of energy transformation even when considering a specific process observed only at the local scale and for a limited period of time.

3. the socio-economic perspective in relation to the definition of energy performance. Production factors – power capacity (technology), human activity (labor), energy carriers, material inputs, water inputs and land uses – are required, in different combinations, by the different sectors of the society to carry out different tasks. Moreover the combination of these factors - technology, human activity, energy, land, water and other inputs - is required not only for producing (in the paid work sector) but also for consuming (in the household sector). Therefore, technical changes and innovation about the production and use of energy carriers imply unavoidable trade-offs between different criteria of performance of the socio-economic systems (e.g. technology vs jobs, profit vs equity, etc.). In relation to this perspective it is essential to be able to integrate the biophysical view adopted when framing the performance using the engineering perspective within a more complex appreciation of the set of relations existing within the different components of the society;

4. the ecological perspective in relation to the definition of energy performance.

The energetic metabolic pattern of society takes place within large scale processes determined by the metabolic patterns of ecosystems embedding the economy and by larger scale biogeochemical cycles taking place in the planet. For this reason, it is essential to include in the analysis dealing with the performance of energy security another dimension of analysis referring to the health of the environment. There is an unavoidable trade-off between improvements in the material standard of living of humans and the reduction of the environmental pressure that humans are representing for the ecosystems in which they live. In fact, the metabolism of energy of modern society is exactly aimed at expressing patterns of energy dissipation that would not be expressed naturally – i.e. without the intervention of humans – by the surrounding ecosystems.

5. the ethical perspective in relation to the definition of energy performance.

The last two of the five factors illustrated in Figure 13 – Factor #4 *the externalization of energy intensive production to other economies*; and Factor #5 *massive policies of credit leverage and quantitative easing* (externalization to future/younger generations) represent two solutions having important ethical implications. In fact, in the first case, the solution implies a systemic externalization of "energy intensive sectors" – e.g. iron and steel, machinery – to emerging economies. This has been an essential strategy making it possible the development of the concept of so-called "knowledge economy" a society expressing a metabolic pattern requiring less energy and material throughput. However, this result is obtained using resources - oil reserves for PES import; land, water, soil and biodiversity for food import; and cheap labor for imported goods and raw materials - of other societies, compromising their options of development (Reinert, 2008). The second solution implies adopting a strategy – making massive quantities of debt - that can be justified only: (i) IF we were going through special temporary crisis (a war, a natural disaster, a major restructuring of the economy); and (ii) IF these resources were used to impose dramatic restructuring to the economy. On the contrary we are making huge quantities of debt just ***to stabilize the status quo***! That is, we use this "virtual money" to pay the pensions and the salaries to the voters of urban democracies with the goal of prolonging the agony of a stagnating economy, without generating any significant change in the characteristics of the existing metabolic pattern. In this way, the present generation (especially the urban elites) are moving the burden of the crisis to the young and future generations that probably will not enjoy the same benign welfare state.

SECTION 2

Practical aspects of a quantitative analysis of the functioning of the energy sector

2.1 An overview of the MuSIASEM approach applied to energy analysis

The MuSIASEM framework was envisioned by Giampietro and Mayumi (2000a, 2000b) and then implemented in a series of books (Giampietro et al. 2012; 2013; 2014) thereafter applied to various cases of the nexus between energy, food, and water by the IASTE group and collaborators (Madrid et al. 2013; Serrano-Tovar and Giampietro, 2014; Velasco-Fernández et al. 2015; Madrid and Giampietro, 2015; Kovacic and Giampietro, 2016).[3] The MuSIASEM approach is used at the moment as the main analytical framework in a large EU project (Moving to Adaptive Governance In Complexity: Informing Nexus Security, funded in the Horizon 2020 program G.A. 689669**).**

In brief, this approach permits to integrate technical, economic, social, demographic, and ecological variables simultaneously in the analysis of the metabolic pattern(s) of modern societies. Its multi scale feature makes it possible the scaling up and or down the characteristics of individual systems/processes/sectors. This in turn allows to study their performances even if the representation across different scales implies the use of non-equivalent data sources when considering analysis carried out at different hierarchical levels (example of this fact have been presented in Section 1).

Relevant for this deliverable and for characterizing energy efficiency from the matrix of production of energy carriers, the MuSIASEM framework can be used to characterize energy production systems (be it for power generation or for oil refinery) adopting a bottom up representation – using information referring to the technical characteristics of the plants used in the energy systems considered – using the concept of processor developed in relational analysis (Louie, 2009). In the rest of this section we provide a few examples of the importance of this framework of analysis referring to the characteristics of the energy sector of EU-28 Countries. MuSIASEM adopts the Flow-Fund model of analysis proposed by Georgescu Reogen (1971) making a distinction between FUND elements and FLOW elements in the quantitative representation. Variables referring to the characteristics of Fund elements describe components that are *reproduced* by the metabolic process and that therefore *remain the same* during the duration of the analysis. Examples of FUND elements are population size, land and/or technological capital, called in the jargon of energetics power capacity. The size of these elements is assumed to remain constant over the duration of a year. Variables referring to the characteristics of Flow elements describe components that are *changing their identity* - they are either consumed or produced - in the duration of the analysis. Examples of FLOW elements are energy, food, raw materials and money. Flow elements

[3] For more information on the Integrated Assessment Group see: http://iaste.info/

have to run through the system to ensure the maintenance and reproduction of fund elements.

Then MuSIASEM establish a series of relations over the characteristics of flow and fund elements defined at different scales and in relation to the definition of different functional compartments of the society using the concept of “processor”. A processor is an expected combination of inputs consisting of fund elements (i.e. labor, technological capital, land uses) and flow elements (i.e., energy, water, and material input) which have to be combined in a given (required) profile in order to be able to express a given activity. An example of the conceptualization of the metabolic pattern which can be used to define the metabolic blueprint of a given processor is given in Figure 13Figure 14.

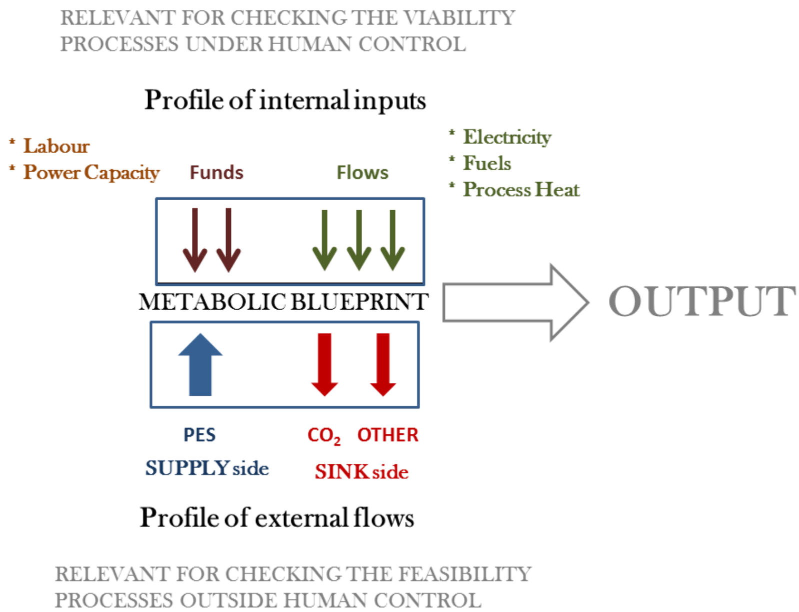


Figure 14 A visualization of the set of relations over the profile of inputs and outputs described using the concept of processor

The concept of processor is analogous to the concept of “enzyme” in “biochemistry” or to the concept of “extended production function” in bio-economic analysis. It makes it possible to establish an expected relation between: (i) a given output, which can be defined either in terms of a given economic activity or a biophysical process; and (ii) a specific profile of requirement of inputs (hours of labor, quantity of technology, kWh of electricity, MJ of fuels, Liters7 of water, etc.). The concept of processor is associated with four key features of relational analysis:

(1) it makes it possible the scaling of information across levels – i.e. in metabolic pathway composed by a series of sequential transformations, the profile of inputs required by a processor expressing a given task can be summed to the profile of inputs required by the other processors expressing the other task. In this way it becomes possible to define an overall profile of requirements of the whole metabolic pathway in term of an aggregate processor;

(2) it makes it possible to integrate the analysis of energy, food and water metabolism in relation to the nexus. In fact additional inputs can be added to the profile of inputs and outputs;

(3) it makes it possible to establish a bridge between: (i) variables referring to processes under human control (labor, technology, electricity, fuels, process heat) - variables that have a relevance in relation to socio-economic processes - on the top in Figure 14. They are important to study the VIABILITY of the tasks considered; and (ii) variables referring to processes outside human control (on the supply side - availability of primary energy sources, other environmental inputs such as water and mineral; on the sink side – availability of sink capacity to absorb emissions and wastes) – variables that have a relevance in relation to ecological processes - on the bottom in Figure 14. They are important to study the FEASIBILITY of the tasks considered;

(4) it makes it possible to establish a bridge between: (i) economic analysis – obtained when considering the monetary values of inputs and outputs; (ii) technical analysis – obtained when considering the biophysical conversions under human control; and (iii) environmental analysis – obtained when interfacing the analysis of external flows with a spatial analysis of the interface with embedding ecosystems.

In this deliverable we deal only with the analysis of the metabolic pattern of energy in relation to the definition and characterization of "efficiency". Therefore we characterize the processors only looking only at internal inputs and external flows associated with energy transformations. That is, in the analysis of the energetic metabolism MuSIASEM describes the characteristics of the processors used in the energy sector using two key fund elements: (i) human activity (measured in hours of paid labor); and (ii) power capacity (measured in kW of technological converter) – Giampietro et al. 2013. In relation to this point, Diaz-Maurin, 2016 has proposed a distinction between: (i) the Power Capacity used in the dissipative compartment associated with purely dissipative end uses (the power capacity is required to consume energy carriers) such as the operation of a car, a refrigerator, a computer; and (ii) power capacity used by processors operating within the energy sector to produce energy carriers. This second type of the fund power capacity can be indicated as Power Capacity Hypercyclic (PCH) flagging is peculiarity of being consumer and producer of energy carriers at the same time.

An example of an application of the concept of processor to the analysis of energy system is given in Figure 15. In this example, we show the conceptual mechanism making it possible the characterization of the metabolic blueprint of an energy system producing energy carriers based on the concept of scaling the metabolic blueprint of processors.

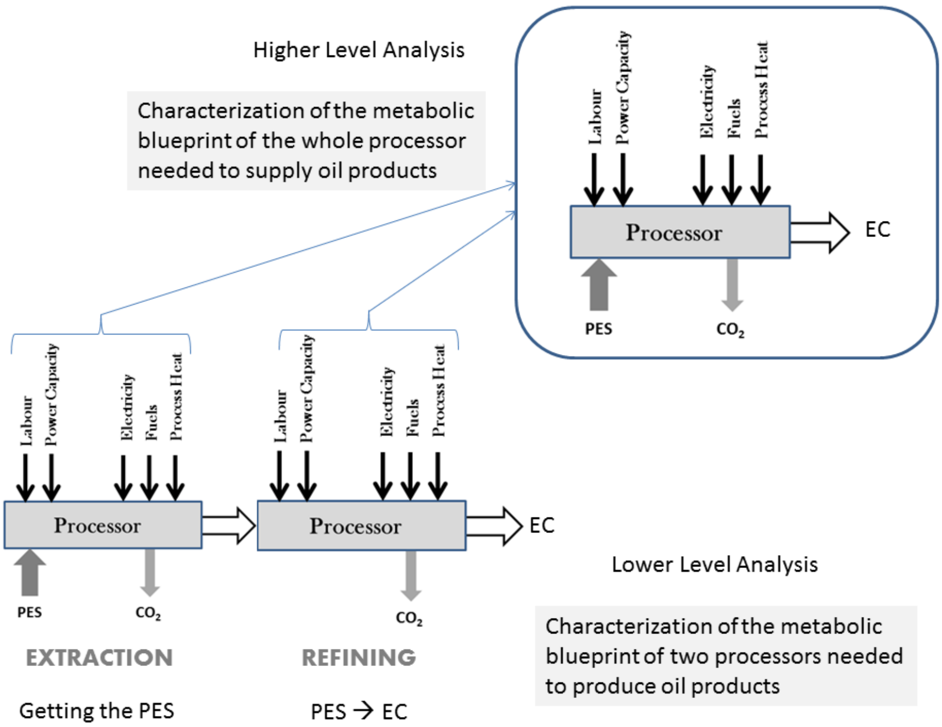


Figure 15 The scaling of the metabolic blueprint of processors within a sequential metabolic pattern

The blueprint of a processor expressing a specific task can be scaled up to characterize the blueprint of the whole sequential process made up of several tasks, by adding the various inputs over the same categories of accounting into the aggregate one. An example of a more elaborated process of scaling applied to the analysis of the Gas and Oil sector of Brazil is shown in Figure 16 and described in Aragão and Giampietro, (2016). We will explain more in detail –in section 2.7 - the nature of the relations established among the various elements presented in Figure 16 when illustrating examples of applications of the quantitative analysis of energy systems, for the moment, the scheme simply illustrates as a set of quantitative characterizations can be organized across different levels and scales. The data arrays are made up of 3 elements - the quantity of labor, fuels and electricity required per unit of throughput (the oil and gas supply) – and are used to describe the characteristics of: (i) specific technologies – e.g. on shore and off-shore extraction plant, or pipelines, ships or trucks used in transportation; (ii) specific functional processes – extraction, transport, refinery; and (iii) the whole sub-sector of Oil and Gas. The information referring to both the size of the technology expressing the function and the relative profile of requirements of labor, fuel, and electricity in the various functional processes can be used to scale-up this characterization to the assessment of a processor referring to the whole sub-sector.

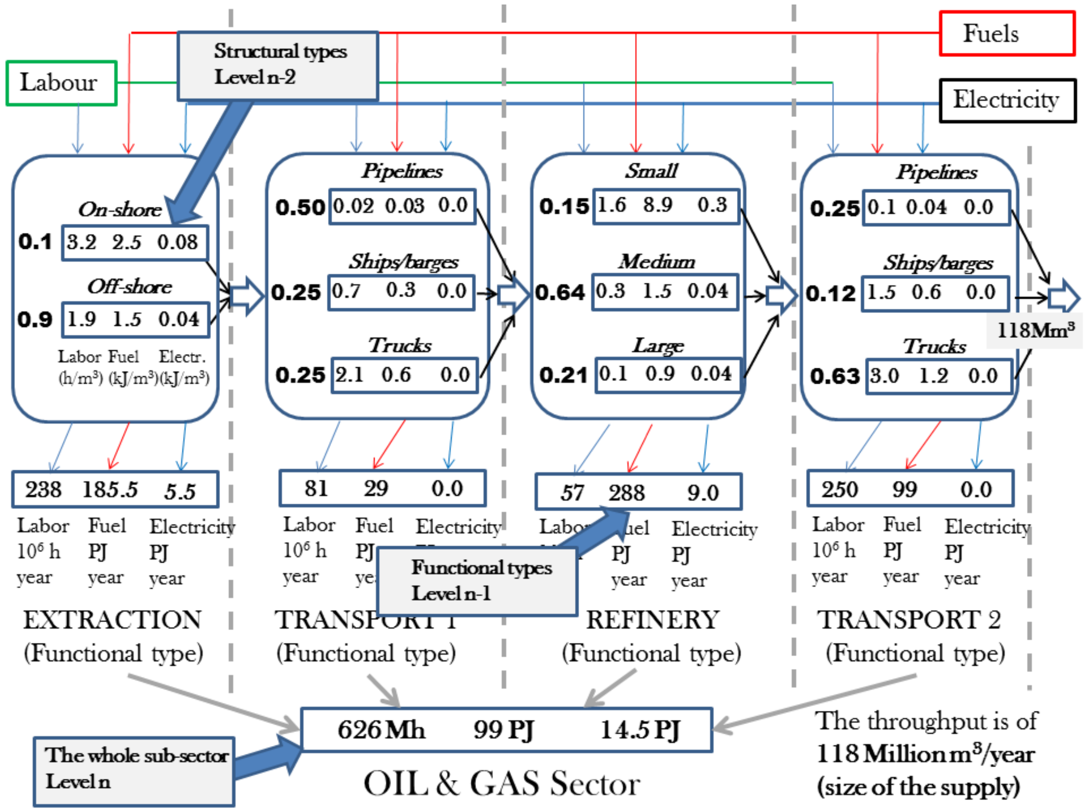


Figure 16 A practical example of scaling of the characteristics of processors defined at different hierarchical levels of analysis (individual plant, functional task, the whole energy system) – (Aragão and Giampietro, 2016)

It should be noted that we can define processors to characterize the production of energy carriers (and other flows) – e.g. “corn produced per hour of labor in monocultures” in the phase of biomass production when dealing with ethanol production or “oil extracted in an off-shore platform” when dealing with oil product production. In the same way we can define processors to characterize the consumption of energy carriers (and other flows) – e.g. “domestic electricity consumption for air conditioning in a house”. By aggregating the characteristics of processors across levels we can arrive to characterize even socio-economic compartments in terms of metabolic rates (examples of this type of comparison have been given in Figure 5 and Figure 6 in Section 1).

The characterization of the economic process in terms of processors requiring funds and flows for their operations makes it possible to individuate key characteristics of the productive side and the consumption side in relation to the possibility of stabilizing a dynamic equilibrium of demand and supply over these two parts of the metabolic pattern.

This problem has been studied in theoretical ecology (Ulanowicz, 1986) in relation to the viability of dissipative metabolic network. In the jargon of theoretical ecology, the productive part is called the *hypercyclic part* – the energy sector consumes energy carriers, but it produces much more energy carriers that it uses. The hypercyclic part, in colloquial terms, means a part of the system that produces a surplus/profit: it provides back to the rest of the system a quantity of energy much larger than the quantity it consumes. The rest of the economy, the consumption part, is called the *purely dissipative part* – it only consumes energy carriers. In colloquial terms, this means that the rest of the system depends and is limited by the characteristics of the hypercyclic part for its level of consumption of energy. Therefore the dynamic equilibrium depends on four factors: (i) the Strength of the Energetic Hypercycle (SEH) – the surplus of energy carriers generated by the hypercyclic part in relation to its own consumption; (ii) the level of consumption of the dissipative part per unit of its size; (iii) the relative size of the hypercyclic part and the purely dissipative part; (iv) the ability of the system to externalize the cost of gathering of PES and the cost of production of EC to other metabolic systems. It is important to be able to check the consequence of the last factor, because externalization is a very effective strategy to boost the Strength of the Energetic Hypercycle. Importing either PES or EC generates a short-cut in the need of carrying out biophysical processes inside the system. In this way, it becomes possible to obtain levels of SEH much higher than those that are possible according to the performance associated with existing technical coefficients.

2.2 Framing the analysis of the characteristics of the energy sector using MuSIASEM

As explained in Section 1 in this deliverable we will only study the characteristics of the production side – the hypercyclic part generating an autocatalytic loop of energy carriers – of the metabolic pattern. That is, we will study the characteristics of the energy sector determining the performance of the supply of EC to the society.

The performance of the energy sector can be analyzed looking at two basic functions it expresses:

1. **Energy Provision –** this function is expressed adopting two distinct strategies: (i) domestic extraction or exploitation of Primary Energy Sources available within the boundary of the system; and (ii) import of Primary Energy Sources and Energy Carriers. It should be noted that European countries are heavily dependent, in general, on this second strategy. Therefore, it is important to assess the **"degree of openness"** of the energy sector of European Countries by looking at how much of the energy carriers used are actually domestically produced vs how much are imported. As discussed in Section 1 this information is important for several reasons: (i) to assess what are the factors determining the energy security; (ii) to assess the role of "imports" and externalization – that can be paid by making debt! – in the overall energy efficiency of EU countries; (iii) the ethical dimension associated with globalization: rich people do use more resources than poor people and this does not reflect natural endowment of resources;

2. **Supply of energy carriers -** this function is expressed adopting different typologies of energy systems in which depending on the nature of the Primary Energy Source available different technological processes are used to convert Primary Energy Sources (whether Fossil or Renewable) into Energy Carriers. These energy carriers are then distributed to the society (which includes also the energy sector itself!) for carrying out the various activities and services associated with the given socio-economic process. The expression of this function depends on two key factors: (i) the feasibility of the supply, determined by external constraints, that is by the characteristics of processes outside human control. The feasibility of the supply depends on the availability of enough PES to be

used by the energy sector; (ii) the viability of the supply, determined by internal constraints, that is by the characteristics of processes under human control. The viability of the supply depends on the availability of enough technological capital, labor and other inputs to be used in the energy sector. Using the jargon of MuSIASEM we can say that this requires the expression of the specific processors needed to guarantee the conversion of available PES into the expected supply of EC.

We can recall here the set of relations over the metabolic pattern of energy illustrated in Figure 13 in Section 1. The catabolic part – or the productive side, or the hypercyclic part - on the left side of the graph - is represented by the energy sector, the sector in charge for the provision of energy and the supply of energy carriers. The supply of energy carriers is used – on the right side of the graph - by the rest of society to express the socio-economic process. The performance of the economic process determines the terms of trade - the overall effect of imports and exports - that in turn will determine the ability of externalizing both: (i) the requirement of resources and environmental services – in relation to feasibility; and (ii) the requirement of fund and flow elements to be used in the processors – in relation to viability. A different view of the same set of relations is described in Figure 17 using a different method of representation (called in the MuSIASEM jargon a grammar) making it possible to focus more specifically on the set of transformations taking place in the energy sector by making a distinction between the factors required to characterize the performance of the system. Looking at the set of relations shown in Figure 17 we can see that:

(i) when looking at energy provision it is possible to track whether the energy sector is operating using foreign resources through imports or local resources in its domestic supply. This analysis is based on a specific distinction between the type of energy forms imported. In fact, imported PES – e.g. oil, uranium, natural gas – make it possible to externalize the requirement of resources (easing up on feasibility) and the requirement of processors (internal constraints) in relation to the extraction and transportation of PES; whereas importing directly EC not only externalize the requirements associated with the provision of PES but also to requirement of the processors needed for producing EC – e.g. the refining of oil into oil products or the production of electricity;

(ii) when looking at the supply of energy carriers it becomes possible to track how much is used as an input and how much is produced as an output in the different energy systems operating in the energy sector. However, this requires considering the mix of PES, the mix of EC and the characteristics of the technology used in the different energy systems. An example of the overview required for this overview is illustrated in Figure 9 of Section 1.

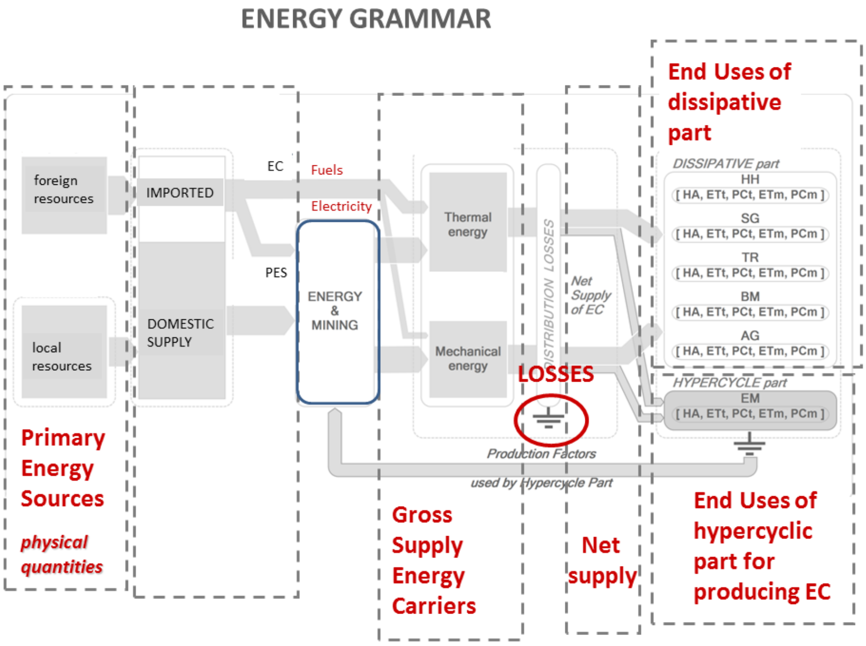


Figure 17 A grammar illustrating the relation over the different categories of accounting useful to characterize the transformations associated with the operation of the energy sector

Power Capacity elements required by the processors operating in the energy sector have to be defined for different types of energy systems. For example, the oil and gas energy system has different typologies of processors (technology). This energy system is associated with a series of functional transformations including: extraction (e.g. off-shore platform, on-shore plants), transportation (e.g. pipelines, trucks), conversion of PES into EC (e.g. large and small refineries). The same applies to nuclear energy system with a different series of specific professors required for the mining of uranium, refining and generation of the fuel, the nuclear plant of power generation, and radioactive waste handling. Therefore there the typologies of fund elements of power capacity (the lexicon of technologies used in the representation of the energy sector) can be associated to both the type of PES and the type of EC. That is there is a standard relation "type of PES → type of EC" that determines the identity of the fund elements of power capacity specifically required for that conversion. This relation can be complicated in case of co-generation, but in general terms we can do general statements about the supply of different types of energy carriers. For example, we can say that, at the moment, in relation to the large scale of supply of liquid fuels the only possible option is the energy system extracting and refining fossil energy. The alternative to fossil energy, biofuel, is still far from being competitive. On the contrary the supply of electricity and process heat can be obtained relying on a larger variety of options of PES and energy systems, both through non-renewable and renewable PES. The concept of processor makes it possible to add to the assessment additional requirements of inputs (both under and outside human control) in the analysis. In fact, depending on the energy system the supply of energy carriers requires not only a specific power capacity type but also a specific amount of labor, hectares of land use (in relation to fund elements) and a given profile of electricity, fuel, heat, water flows (in relation to flow element). A processor makes it also possible to associate an expected level of greenhouse gas emissions to the operation of a processor within the chain of transformation taking place in an energy system.

So in this deliverable we will only focus on two types of information relevant for the assessment of its performance:

* **about the flows exchanged with the environment outside human control** – this assessment refers to: (i) the consumption of PES on the supply side – how much the metabolic pattern is dependent on the availability of PES for its feasibility; and (ii) the emission of GHG and other dangerous emissions on the sink side – how much the metabolic pattern is dependent on the availability of ecological service providing sink capacity for its feasibility;

* **about the flows processed in the energy sector** – this assessment refers to: (i) the requirement of fund elements in the processors – how much labor and technical capital (power capacity) is needed for the operation of the energy systems; and (ii) the requirement of flow elements in the processors – how much energy carriers are needed as input.

2.3 Data Sources

The collection of information regarding Fund and Flow elements used in the energy sector has been obtained organizing data on non-equivalent categories: (i) Primary Energy Sources (whether domestically produced or imported) and (ii) Energy Carriers divided in electricity, heat or petroleum products (whether domestically produced or imported). Data have been obtained from the following data sources:

* International Energy Agency (http://www.iea.org/sankey/) organized in sankey flow diagrams to have a cross country comparison profile for the EU countries as well as other countries such as China (in future deliverables);

* the Eurostat database for process specific data such as electricity, gas, petroleum products used in CHP and Heat Plants, Petroleum Refineries, Coke Ovens, Oil and Gas Extraction, Coal Mines and Nuclear Industry, the energy balances - annual data [nrg_100a] (http://ec.europa.eu/eurostat/data/database);

* the European Environmental Agency Greenhouse Gas Emissions [env_air_gge] database for data regarding emissions for energy provision processes (or referred to as Energy Industries sub-divided into three bulk categories - as Public Electricity & Heat Prod, Petroleum Refining and Manufacture of Solid Fuels and Other Energy Industries) (http://www.eea.europa.eu/data-and-maps/);

* Enipedia database (http://enipedia.tudelft.nl)[4] for data about Power Capacities and Power Generation Technology (fund elements) by country by fuel type. Enipedia is an extensive, up-to-date, collaborative effort that serves both as a database and a wiki, bringing together data and information on all the world's power plants, for querying,

[4] C.B.Davis, A. Chmieliauskas, G.P.J. Dijkema, I. Nikolic (2015), Enipedia, http://enipedia.tudelft.nl, Energy & Industry group, Faculty of Technology, Policy and Management, TU Delft, Delft, The Netherlands.

visualization and for analysis. From this database it is possible to gather information on the state of electric power supply, technologies employed and conversion efficiencies;

2.4 A quantitative analysis of the openness of EU 28 countries in relation to the provision of PES

An overview of the total magnitude of imported primary energy sources in EU 28 is illustrated in Figure 18 using data for the year 2013 from the International Energy Agency (http://www.iea.org/sankey/) database. Two well known facts are clearly illustrated by this figure: (i) because of its size Germany leads the ranking of countries in terms of absolute quantity; (ii) crude oil imports occupy most of the primary energy provision demand.

In terms of Crude Oil Production in the EU 28 countries analysed, only Denmark has a domestic production 121% larger than the domestic consumption (making it possible a 21% of export). All the other countries are NET importers. In relation to the relevance of domestic production, the UK shows reaches a 63% of crude oil domestic production. However, these values should be crosschecked, because the ownership of companies registered in these countries may imply an overestimation due to quantities of oil extracted/produced elsewhere. The remaining 90% of the EU countries in the sample have less than 5% of local crude oil production. On the contrary, coal production, with a longer history in terms of production in the EU 28, dominates in several of the Eastern European countries where there is a stronger tradition of domestically producing coal, where is still provides well over 80% of domestic consumption (Poland, Romania, Bulgaria, Czech Republic, Estonia, Greece, Slovenia). Natural Gas is foremost led by the Netherlands (or companies registered in the Netherlands) providing around 186% of domestic consumption and therefore making possible exports. Other countries such as Bulgaria, Denmark, Greece and Ireland, Slovenia can cover their domestic consumption of gas through domestic supply. Biofuels and Waste when considered as energy sources are domestically produced and consumed.

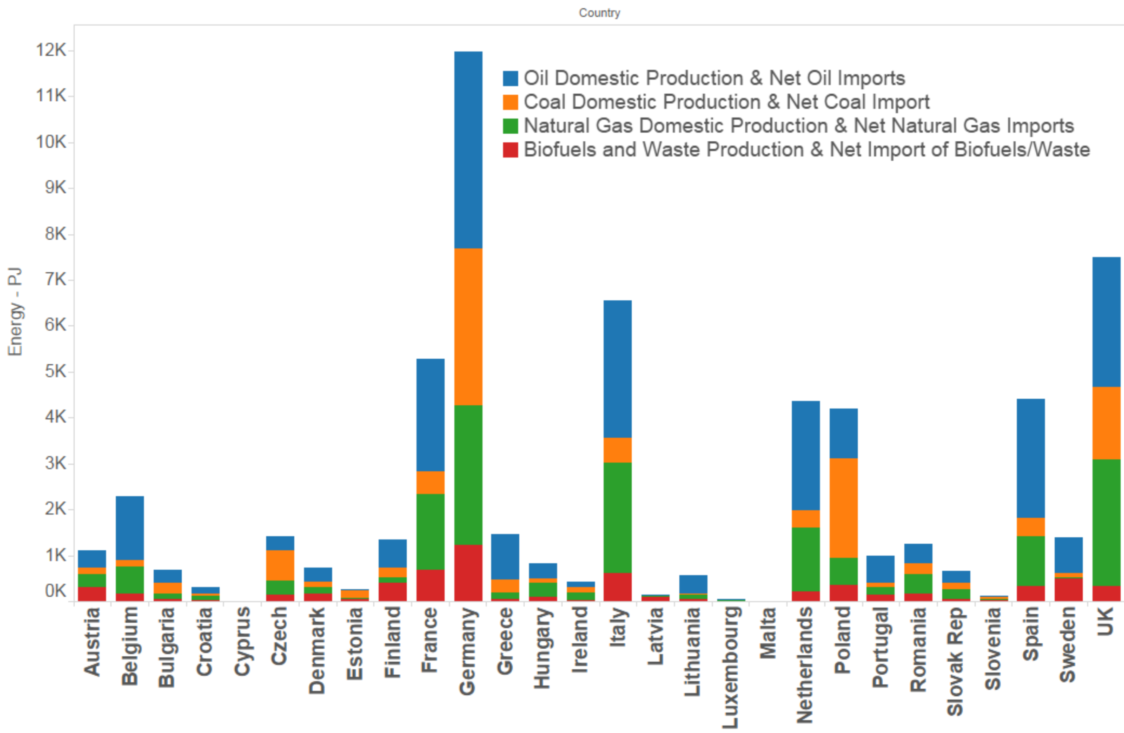


Figure 18 Overview of the import of PES (by type) in EU 28 countries

As discussed earlier it is important to know not only the amount of import required by the energy sector of a country in absolute terms, but also how do these imports compare with the domestic production, to assess the level of "externalization" of the requirements relevant for the definition of external (availability PES) of and internal (requirement of flow and fund for the operation of the processors) constraints. Therefore, using the same source, data of Figure 18 have been re-categorized under two different categories: (i) Domestic Production; and (ii) Net Import in order to visualize how much the imported forms of energy are covering the internal consumption in the EU 28 countries. This information is given in Table 1 (below) in terms of how much (% total) these primary energy sources countries are imported (calculated in NET terms) or produce locally. Negative values in the table refer to quantities that are exported.

Table 1. Domestic production and Net Import for Oil, Coal, Natural Gas, Biofuel/waste

EU 28
Year 2013

Country	Oil Total - PJ	Coal Total - PJ	Natural Gas Tot..	Biofuels/ Waste - ..
Austria	384	132	294	299
Belgium	1,385	128	606	155
Bulgaria	284	241	103	54
Croatia	147	31	96	32
Cyprus	0	0	0	2
Czech	297	664	300	152
Denmark	307	119	147	158
Estonia	0	185	23	50
Finland	633	212	120	389
France	2,464	495	1,633	695
Germany	4,281	3,405	3,060	1,216
Greece	983	291	136	52
Hungary	321	96	324	86
Ireland	126	115	162	19
Italy	2,989	547	2,401	618
Latvia	0	3	58	83
Lithuania	409	12	91	57
Luxembourg	0	2	37	7
Malta	0	0	0	0
Netherlands	2,386	379	1,384	213
Poland	1,085	2,166	588	351
Portugal	595	106	160	140
Romania	421	239	412	170
Slovak Rep	280	141	202	49
Slovenia	0	56	29	29
Spain	2,602	391	1,095	327
Sweden	783	84	40	485
UK	2,816	1,596	2,754	326

Country	Oil Domestic Production	Net Oil Imports	Coal Domestic Production	Net Coal Import	Natural Gas Domestic ..	Net Natural Gas Imports	Biofuels and Waste Production	Net Import of Biofuels/..
Austria	10%	90%	0%	100%	16%	84%	83%	17%
Belgium	0%	100%	0%	100%	0%	100%	82%	18%
Bulgaria	0%	100%	83%	17%	9%	91%	93%	7%
Croatia	17%	83%	0%	100%	66%	34%	99%	1%
Cyprus	0%	0%	0%	100%	0%	0%	40%	60%
Czech	4%	96%	112%	-12%	3%	97%	94%	6%
Denmark	122%	-22%	0%	100%	122%	-22%	69%	31%
Estonia	0%	0%	100%	0%	0%	100%	99%	1%
Finland	0%	100%	34%	66%	0%	100%	96%	4%
France	2%	98%	2%	98%	1%	99%	97%	3%
Germany	3%	97%	55%	45%	12%	88%	96%	4%
Greece	0%	100%	97%	3%	0%	100%	88%	12%
Hungary	12%	88%	70%	30%	20%	80%	94%	6%
Ireland	0%	100%	47%	53%	4%	96%	81%	19%
Italy	8%	92%	0%	100%	11%	89%	80%	20%
Latvia	0%	0%	3%	97%	0%	100%	95%	5%
Lithuania	1%	99%	8%	92%	0%	100%	88%	12%
Luxembourg	0%	0%	0%	100%	0%	100%	66%	34%
Malta	0%	0%	0%	0%	0%	0%	41%	59%
Netherlands	3%	97%	0%	100%	187%	-87%	86%	14%
Poland	4%	96%	110%	-10%	27%	73%	98%	2%
Portugal	0%	100%	0%	100%	0%	100%	97%	3%
Romania	40%	60%	82%	18%	87%	13%	95%	5%
Slovak Rep	3%	97%	17%	83%	2%	98%	96%	4%
Slovenia	0%	0%	81%	19%	0%	100%	92%	8%
Spain	1%	99%	19%	81%	0%	100%	90%	10%
Sweden	0%	100%	9%	91%	0%	100%	97%	3%
UK	63%	37%	20%	80%	50%	50%	76%	24%

Table 1 – Domestic Production and Net Import for Oil, Coal, Natural gas, Biofuel/waste

2.5 A quantitative analysis of the openness of EU 28 countries in relation to the supply of Energy Carriers

Here, we consider “Electricity” and “Oil products” as the foremost types of energy carriers. Here, we provide in Figure 19, in analogy to what done in Figure 18, an overview of the amount Electricity and Oil Products imported by the EU 28 countries in total aggregate terms (the size of the bar) and divided by category (the different colors of the sections of the bars).

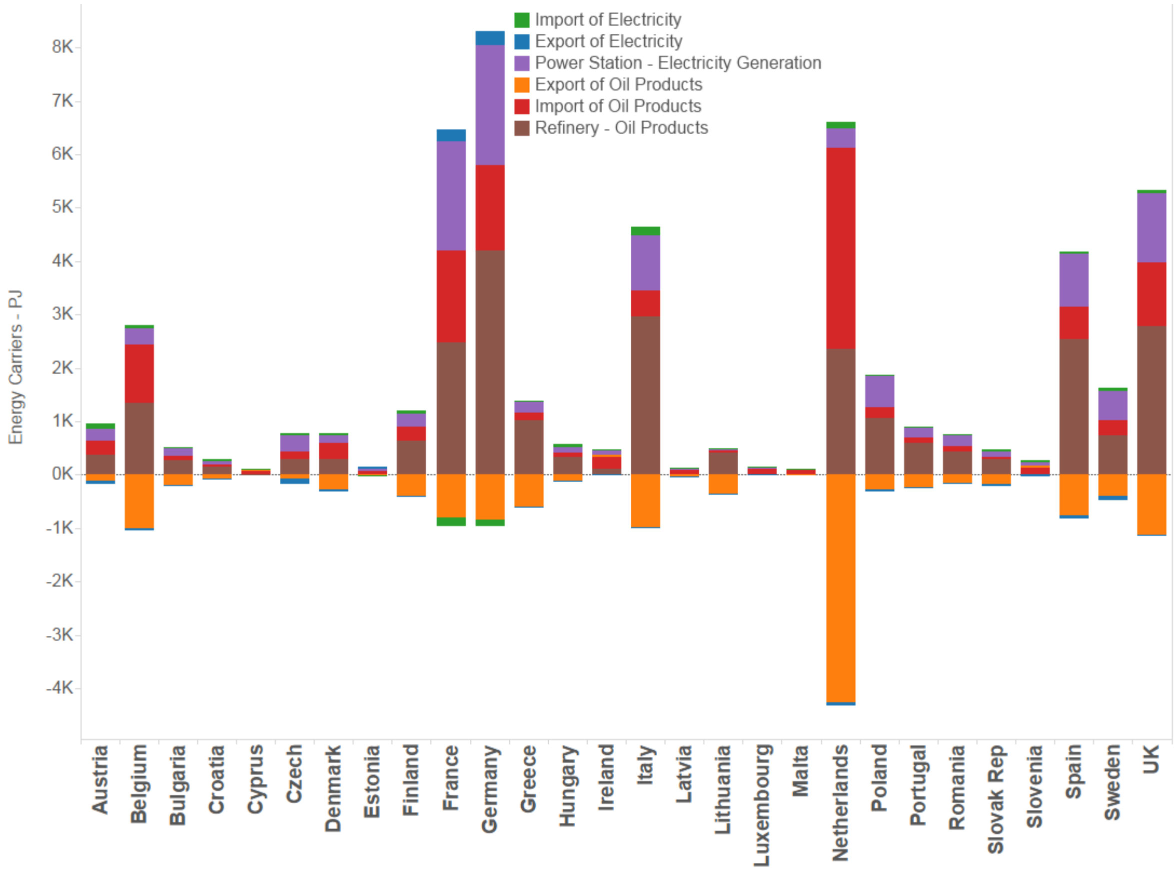


Figure 19 The amount of energy carriers (electricity and fuels) imported/exported by EU 28 countries

Also in this case it is important to analyze the relative importance of domestic supply and import in the overall supply of electricity domestically consumed in the sample of EU 28 countries. This information is given in Table 2. The data set presented in Table 2 renormalizes the assessment of each one of the two carriers to a sum of 100%, indicating whether the electricity and oil products are imported from the international market or are domestically produced. Once again, data have been obtained from the International Energy Agency (http://www.iea.org/sankey/) database for the year 2013 and re-categorized under the two broader divisions of Domestic Production or Net Import for each carrier. According to the data in Table 2, in the year 2013, small countries tend to import more than big countries. For example, Luxembourg imported the majority of its electricity use (73% in 2013) directly from the EU grid. Other countries like Cyprus or Malta, due to their isolation have no such spatial advantage and connection to a central grid therefore have to produce 100% of their electricity within national borders. Both in Malta and Cyprus most electricity is generated by power stations running on "imported oil products". In this case this "domestic production of electricity" presents a double burden: (PES → EC_{fuel}, implying a first energetic cost of transformation and EC_{fuel} → $EC_{electricity}$ implying a second energetic cost of transformation) because energy carriers are used to produce a different type of energy carrier.

Table 2. Energy Carriers imported/exported by EU 28 countries

EU 28
Year 2013

Country	Electricity Total - PJ	Oil Products Total - PJ
Austria	259	630
Belgium	330	2,442
Bulgaria	133	353
Croatia	64	195
Cyprus	15	96
Czech Republic	249	435
Denmark	129	604
Estonia	35	70
Finland	313	890
France	1,868	4,206
Germany	2,143	5,787
Greece	212	1,165
Hungary	152	411
Ireland	100	332
Italy	1,189	3,453
Latvia	27	98
Lithuania	40	453
Luxembourg	24	118
Malta	8	96
Netherlands	429	6,122
Poland	574	1,256
Portugal	192	693
Romania	204	527
Slovak Republic	103	340
Slovenia	53	138
Spain	982	3,136
Sweden	515	1,021
Turkey	891	1,899
United Kingdom	1,335	3,978

Country	Electricity from Power Station	Electricity Import (Net)	Oil Products from Refinery	Oil Products Import (Net)
Austria	90%	10%	61%	39%
Belgium	89%	11%	55%	45%
Bulgaria	117%	-17%	78%	22%
Croatia	75%	25%	74%	26%
Cyprus	100%	0%	0%	100%
Czech Republic	124%	-24%	68%	32%
Denmark	97%	3%	50%	50%
Estonia	137%	-37%	0%	100%
Finland	82%	18%	71%	29%
France	109%	-9%	59%	41%
Germany	105%	-5%	72%	28%
Greece	97%	3%	87%	13%
Hungary	72%	28%	79%	21%
Ireland	92%	8%	35%	65%
Italy	87%	13%	86%	14%
Latvia	82%	18%	0%	100%
Lithuania	38%	62%	89%	11%
Luxembourg	27%	73%	0%	100%
Malta	100%	0%	0%	100%
Netherlands	85%	15%	39%	61%
Poland	103%	-3%	85%	15%
Portugal	95%	5%	85%	15%
Romania	104%	-4%	82%	18%
Slovak Republic	100%	0%	83%	17%
Slovenia	108%	-8%	0%	100%
Spain	102%	-2%	81%	19%
Sweden	107%	-7%	73%	27%
Turkey	97%	3%	54%	46%
United Kingdom	96%	4%	70%	30%

Other countries such as Bulgaria, Czech Rep, Estonia, Slovenia and Spain produce more electricity to the grid than local demands therefore are net exporters of electricity. Importing electricity and or oil products might increase the efficiency of an energy sector, since the biophysical cost of transforming and producing electricity or refining oil is not carried out within national borders. However, when considering the different criteria of performance discussed in Section 1, this cost shifting to other Socio-Ecological Systems has several implications: (i) it reduces the level of energy security, making more and more dependent the country on the market and on the exporting countries; (ii) the biophysical externalization of production costs - such as maintaining power plants or refineries – to other economies pushes them to become more resource-intensive adopting more environmentally-intensive processes and emissions; (iii) the increased level of transportation of goods translates into a larger environmental impact; (iv) the existing diversity in the level of social protection of lower classes can result also in a social cost shifting of the burden associated with the strategy of profit maximization in resources extraction.

Then, the “energy producing” countries, will have to invest a larger fraction of their fund and flow elements (labor, technology and other inputs) in the processors needed for extracting PES and transforming and distributing EC in the energy sector. This increased investment of fund and flow elements in the energy sector (the hypercyclic part) implies a reduction in the amount of flow and fund elements that can be invested in the purely dissipative compartment, where the activities referring to the material standard of living of the people take place. That is, it is likely that in exporting countries the high revenues of oil will generate inequity in the distribution of the profit and hamper the distribution of flow and fund elements on those activities more benign for the well-being of the population. On the contrary, countries depending heavily on imports can divert the resources (fund and flow elements) that would be required to produce energy carriers in consuming energy carriers. In this way they can produce and consume more goods and services (rather than producing energy carriers). Moreover, in this way, they can escape the obvious external constraint of not having fossil energy resources in the first place.

2.6 Using MuSIASEM to provide a quantitative analysis of the effect of “externalization” of external and internal biophysical costs through imports

As illustrated in Figure 15 and Figure 16 an energy system producing energy carriers (either oil based fuels or electricity) can be represented as a sequential metabolic pathway in which different processors are guaranteeing the expression of specific activities in each step of the chain. By using this approach, it becomes possible to compare the performance of different energy systems – e.g. producing electricity either with Nuclear Energy Plants or Coal Fired Plants. A conceptualization of how to carry out a quantitative comparison based on the concept of processors is illustrated in Figure 20.

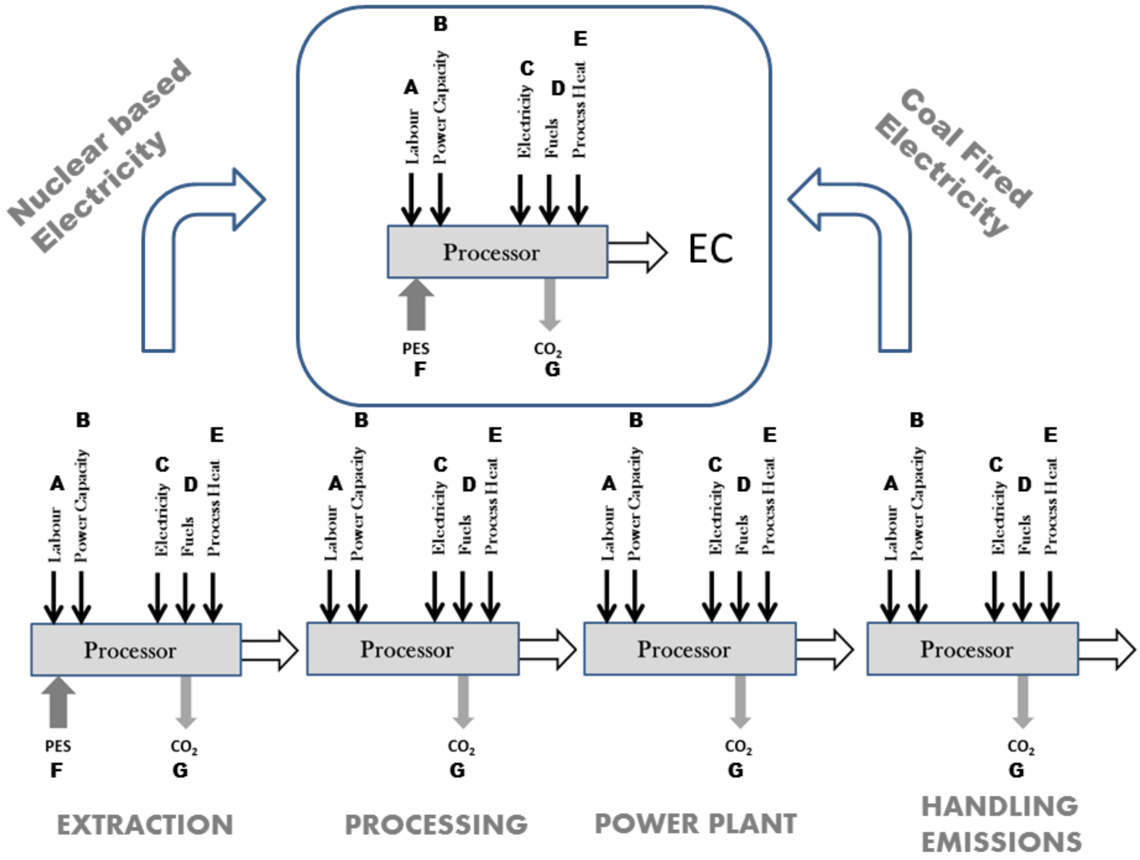


Figure 20 Characterization of the metabolic blueprint of an energy system supplying electricity (used to compare Nuclear Energy and Coal Energy) based on the concept of processors

By adopting the scheme illustrated in Figure 20, we can scale he information about the characteristics of the various individual steps of the sequential process: (i) extraction - for uranium ore and coal; (ii) processing – for generating the nuclear fuel and the coal fuel, (iii) the generation of electricity in the power plant – for handling properly the different types of fuels; (iv) the handling of the emissions – e.g. facilities for handling nuclear wastes versus scrubbers to reduce emissions. In this way we can establish a “semantic” bridge across quantitative information describing the characteristics of the two energy systems (e.g. PES → EC: nuclear energy used to produce electricity, or PES → EC: coal energy used to produce electricity) providing: (i) a common template for describing the metabolic blueprint of the individual steps of the sequential pathway; and (ii) a common definition of functional processes generating the same final output (electricity supply). A detailed example of the type of comparison illustrated in Figure 20 is given in Diaz-Maurin and Giampietro (2014).

The mechanism of scaling illustrated in Figure 20 is self-explanatory. In order to assess the overall labor demand (the arrow labelled **A**) one has to sum all the arrows labelled **A** in the various processors belonging to the same sequential pathway. In order to assess the overall electricity consumption one has to sum the arrows labelled **C** and so on. By repeating this operation for all the flows of inputs and outputs it is possible to characterize a processor referring the characteristics of the whole sequential pathway, that is reflecting the metabolic blueprint of the different processors (described by intensive variables flow/fund ratios) whose information is scaled by the quantity of supply that each processor has generated.

Typologies of energy systems can be associated to the definition of a series of functional processors determining the specific set of transformations associated with the final supply of energy carrier. In the case one wants to analyze the supply of oil products (liquid fuels) one can use the scheme of analysis illustrated in Figure 21. The scheme of analysis is exactly similar to the characterization illustrated in Figure 20. The only difference is given by the labels given to the activities carried out in the different functional processors in the sequential pathway.

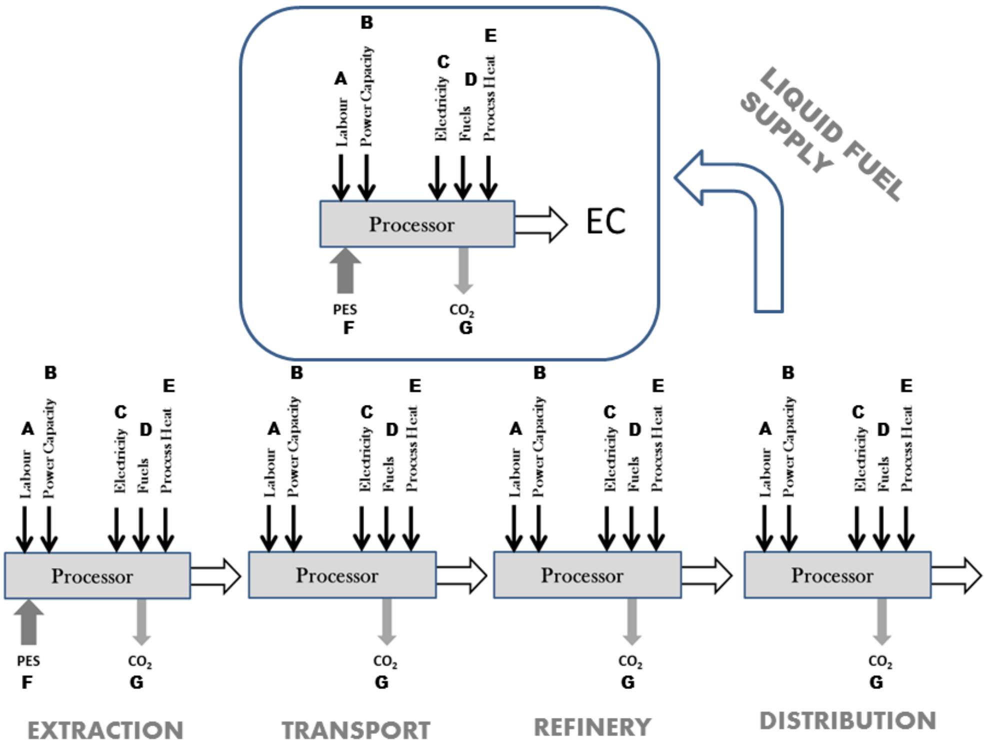


Figure 21 Characterization of the metabolic blueprint of an energy system supplying liquid fuels (here applied to a system using Fossil Energy as PES) based on the concept of processors

By using this approach it becomes possible to study the effects that imports have on the overall performance of the supply of energy carriers. In fact, importing a certain quantity of a given PES or a given EC implies replacing a certain quantity of activity of the processors that would be required to generate domestically that particular flow. The effect of the externalization obtained through export depends on the specific functional steps that are replaced by the imports.

1. if rather than extracting and transporting PES the energy sector imports the PES from elsewhere, then this externalization will save: (i) a quantity of internal inputs: the quantities labelled A, B, C, D, E; and (ii) a quantity of external inputs relevant for defining external constraints: F on the supply side (do we have enough PES? At which speed are we emptying the stocks?) and G on the sink side (what is the load of emissions? Which type of emissions?).

These saving can be calculated after: (i) defining the functional processors no longer required because of the imports – in the case of fossil energy this would be "extraction" and "transport"; (ii) defining the metabolic blueprint of the "virtual processor" whose activity is required to produce the imported PES – in the case of fossil energy this would be the metabolic blueprint of the processor "extraction" and "transport", provided in terms of intensive variables – technical coefficient, a profile of requirement per unit of supply; (iii) calculate the different quantities associated to the metabolic pattern - internal inputs labelled as A, B, C, D, E; and external flows labelled as G and F- that have to be scaled-up starting from the metabolic blueprint of the virtual processor multiplying the requirement per unit by the quantity of imports. An illustration of this situations is given in Figure 22.

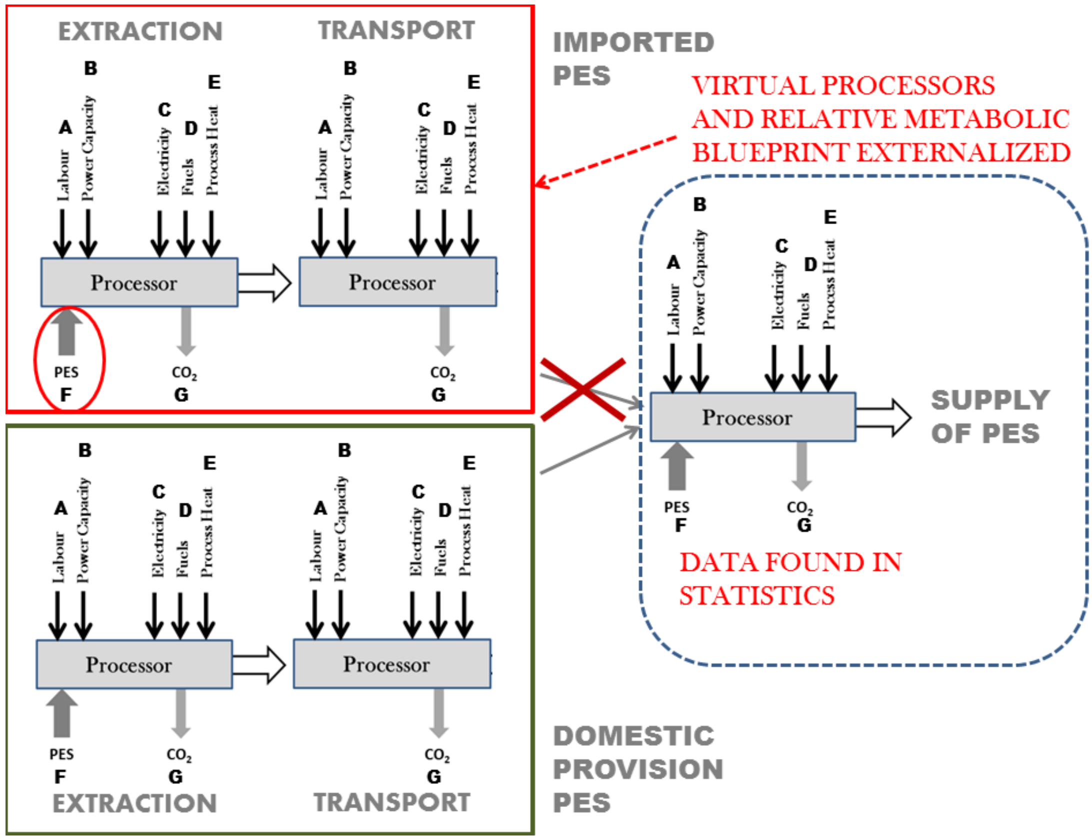


Figure 22 Studying the effects of the import of PES in a given energy system producing EC.

As illustrated in Figure 22 importing PES has the main goal of escaping the external constraint associated with the availability of PES – it reduces, by eternalization, the requirement of the arrow labelled F in the processor of EXTRACTION. As discussed before when looking at the data relative to EU 28 in relation to liquid fuel production this is the most popular solution in Europe. Other savings associated with this solution are related to: (i) the reduction in the use of internal inputs – both fund and flow elements - that would be required to operate the processors dealing with the extraction (or more in general the exploitation) of PES; and (ii) emissions of CO_2 and other GHG to which one should also add other waste outflows (e.g. spills, contamination of water, spreading of pollutants) that affect locally the area of extraction of PES.

2. if rather than extracting and transforming PES into EC the energy sector imports directly the EC from elsewhere, then we will be in the exact situation as in the previous case: (i) the externalization will save both internal inputs and external flows; (ii) in order to assess the effect of this externalization we have to define the functional processors replaced by the imports, using the knowledge of the metabolic blueprint of the required processors to calculate the size of the processors required to produce the imported EC to calculate the quantities of inputs and external flows saved by the imports. The direct import of energy carriers – i.e. liquid fuels and electricity – has the same effects discussed in Figure 22. The only difference is that it further increases the level of externalization in the requirement of internal inputs and external flows.

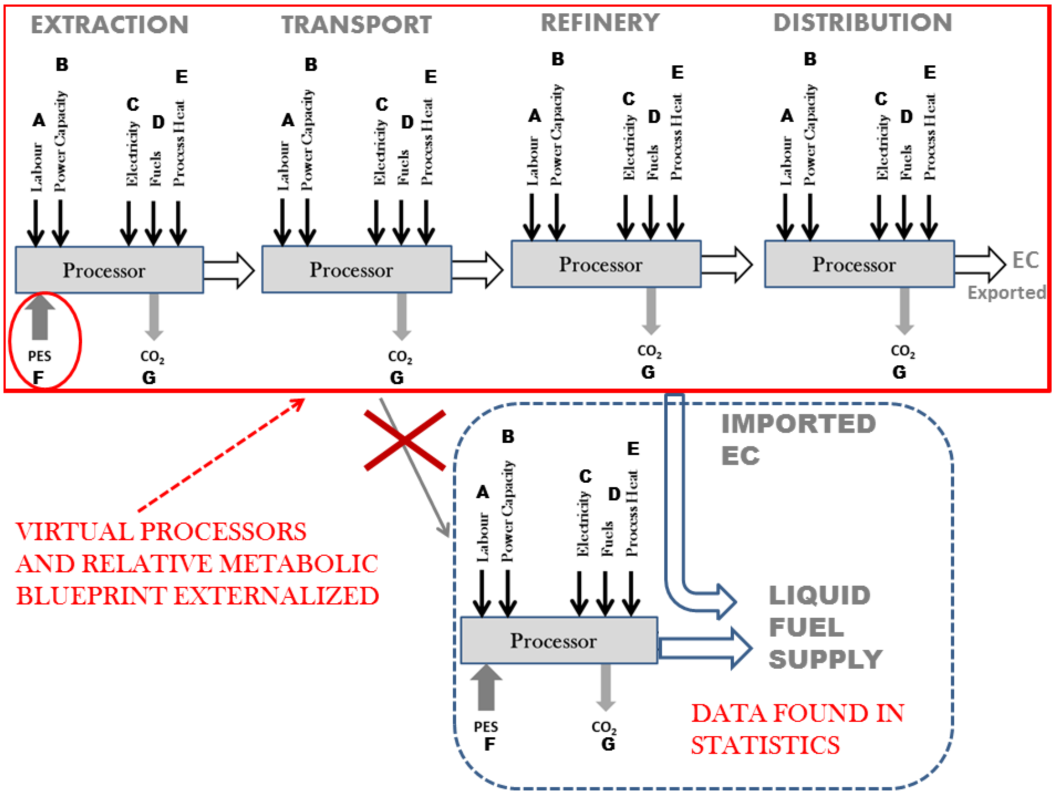


Figure 23 Studying the effects of the imports of EC in a given energy system producing EC

The examples illustrated in Figure 22 and Figure 23 are important because they show that when using national statistical data to study the energy transformations taking place in the energy sector, the information referring to the metabolic blueprints of the processors producing the imported PES or imported EC is not considered. This can generate confusion, because the energy sectors of modern countries are expressing all the steps included in the different energy systems – i.e. extraction, transport, refining, distribution, etc. Therefore, if we use the method of dividing the supply by the inputs required we can generate misleading assessments about the performance of the system. The performance of an energy sector is dramatically boosted – as illustrated in Figure 23 by imports. When comparing the total supply of EC (obtained by mixing together the domestic produced and the imported EC) to the profile of inputs used in domestic production we can get a performance that is simply not compatible with existing technologies. This is to say, that if we do not assess the level of externalization of an energy sector and its implications in determining its biophysical performance, it is absolutely impossible to assess – using statistical data – the “efficiency” or not even the “input/output” of the different energy systems.

Like in the case of the Pulp and Paper subsector discussed in Section 1, we cannot compare the energy system generating liquid fuels from Fossil Energy PES of three different countries, if one of the countries produces everything inside its borders, another imports all the EC as such, and the last one produce all the EC it consumes but from imported PES.

2.7 Examples of assessments of the effect of the externalization provided by import using energy statistics

In this section we present a few examples of quantitative assessments of the effect of externalization using data referring to EU 28. This exercise has three goals: (1) to show that this type of analysis is possible; (2) to show that this analysis cannot be done using only energy statistics; and (3) to show that statistics would become much more robust if they would be better integrated in a relational analysis of the energy sector that includes also recording the fund elements (power capacity), rather than only flow elements (the quantity of energy flowing). The examples of analysis illustrate the application of the theoretical approach presented in Figure 22 and Figure 23 to two individual tasks of a sequential pathway producing liquid fuels from fossil energy. The sequential pathway is illustrated in Figure 21, the two functional tasks considered are: (i) oil and gas extraction; (ii) refining. With these practical examples we want to flag the complexity of the type of energy accounting that would be required to generate information useful to discuss energy policy and to formulate energy directives. In addition, we want also to flag a few current shortcomings of the quantitative information that is used right now to frame the analysis of the performance of the energy system

2.7.1 Example of analysis of an individual task: Oil and Gas extraction

The domestic production of Oil and Gas in the EU28 in the year 2013 is illustrated in Figure 24.

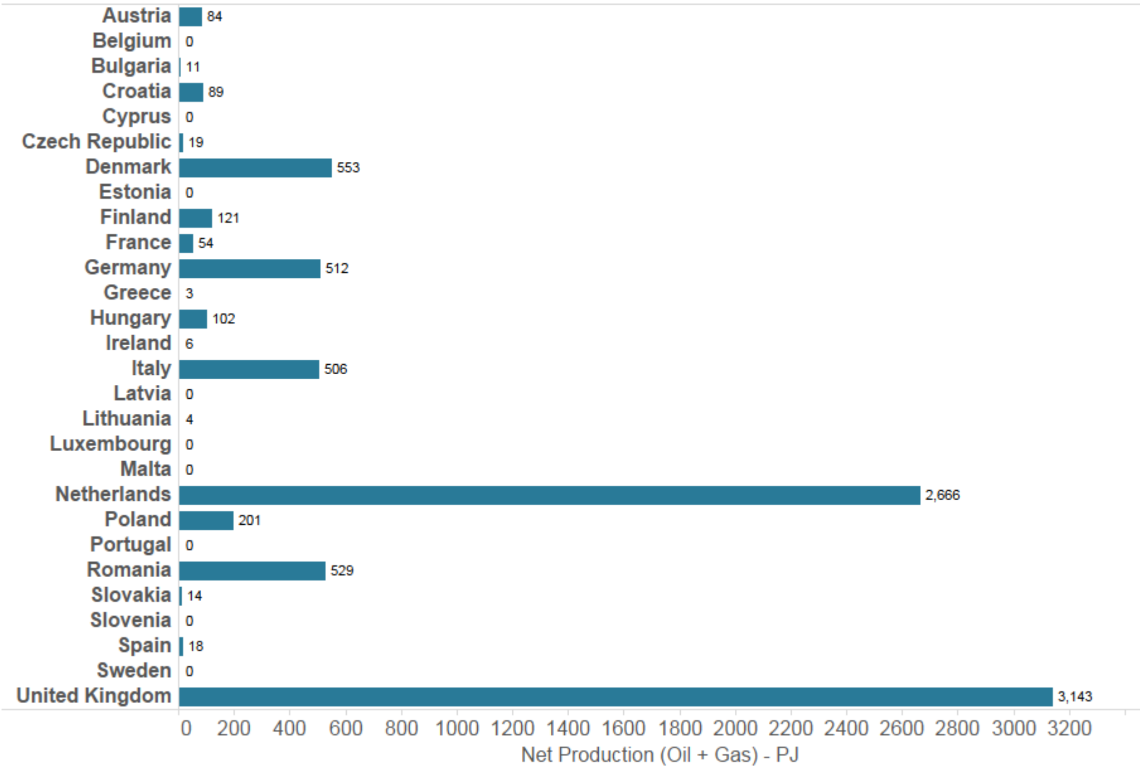


Figure 24 Domestic production of Oil and Gas in EU 28 (2013)

According to the data found in statistics we can calculate the emissions generated by this extraction considering the amount of fossil energy spent in the processors operating in the domestic supply. This would be the assessment of the flow labelled as G in the right box of Figure 22. These calculations are given in Figure 25.

Starting from the amount of oil and gas imported by the different countries – illustrated in Figure 26 – we can calculate, using the rationale of the processors presented earlier, “virtual quantities” of inputs and outputs to be invested in the activity “extraction” that the import of oil and gas implies.

Finally, we can calculate how much input of thermal energy (the arrows labelled D + E in Figure 22) is saved because of this import, using the following procedure: (i) calculation of actual ratio between the amount of oil and gas extracted (output) and the energy input of thermal energy getting into the process of extraction in each country (input); then (ii) using this output/input ratio we calculated how much input would have been required to generate the same quantity of imported oil and gas. Then the assessment of the “virtual” amount of thermal energy input (arrows labelled D + E in Fig. 21) embodied in the imports of oil and gas can be calculated from the knowledge of the processor. The results are given in Figure 27.

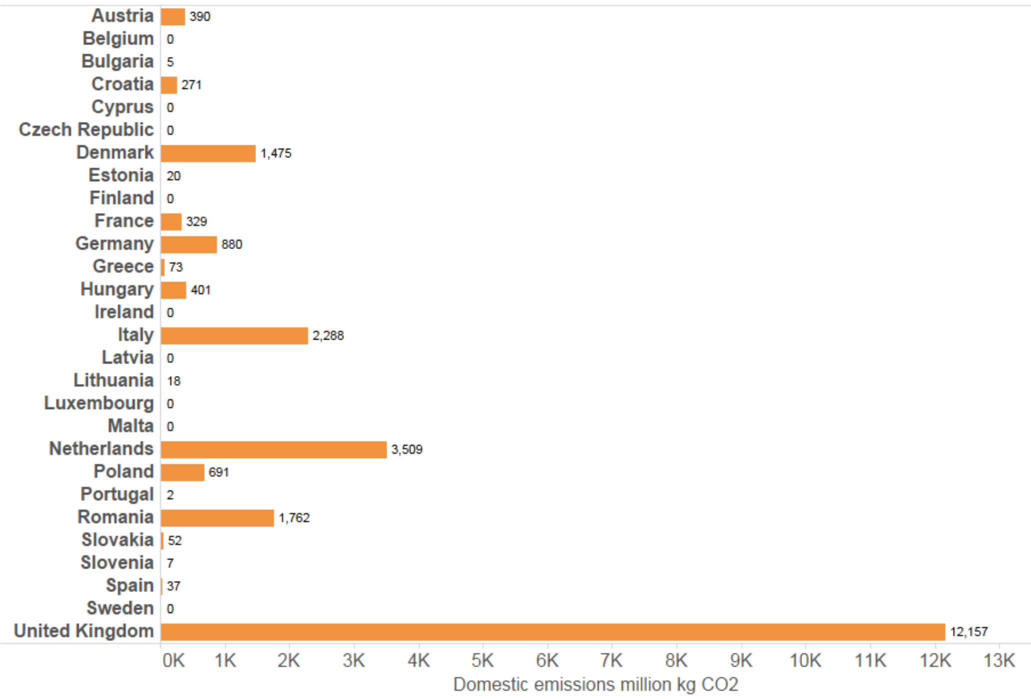


Figure 25 Calculated emissions for the domestic extraction of oil and gas, from the consumption of fossil energy in this activity (in million kg of CO2)

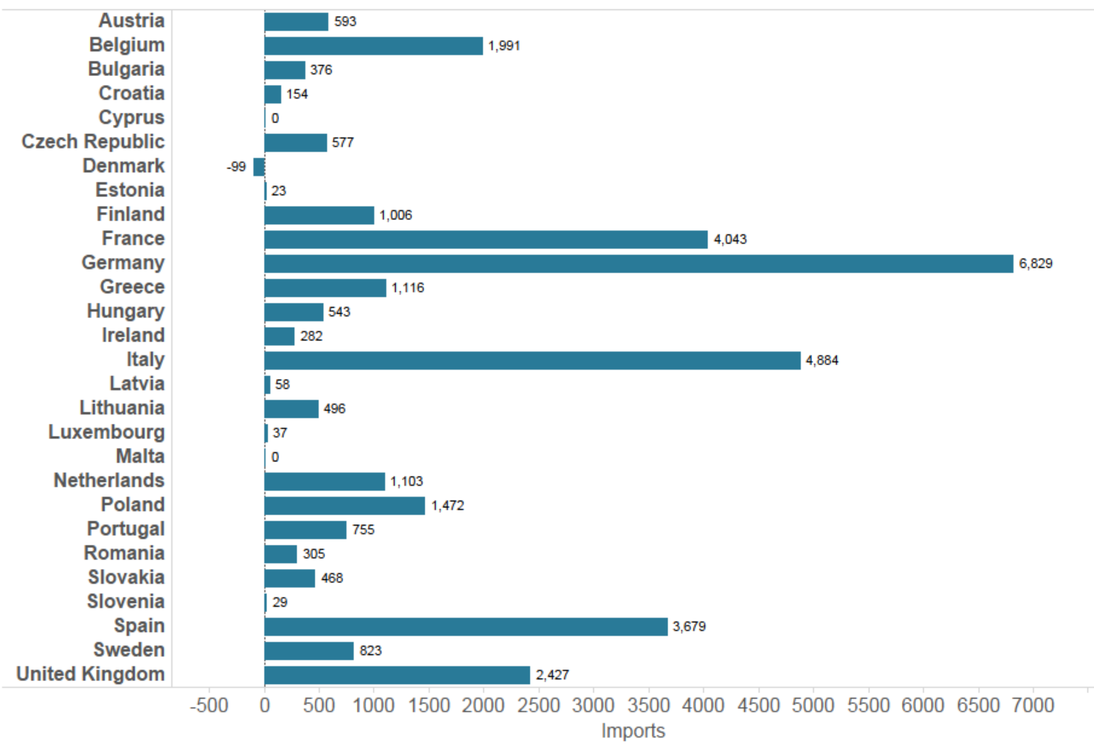


Figure 26 Imports of oil and gas in EU 28 (PJ in 2013)

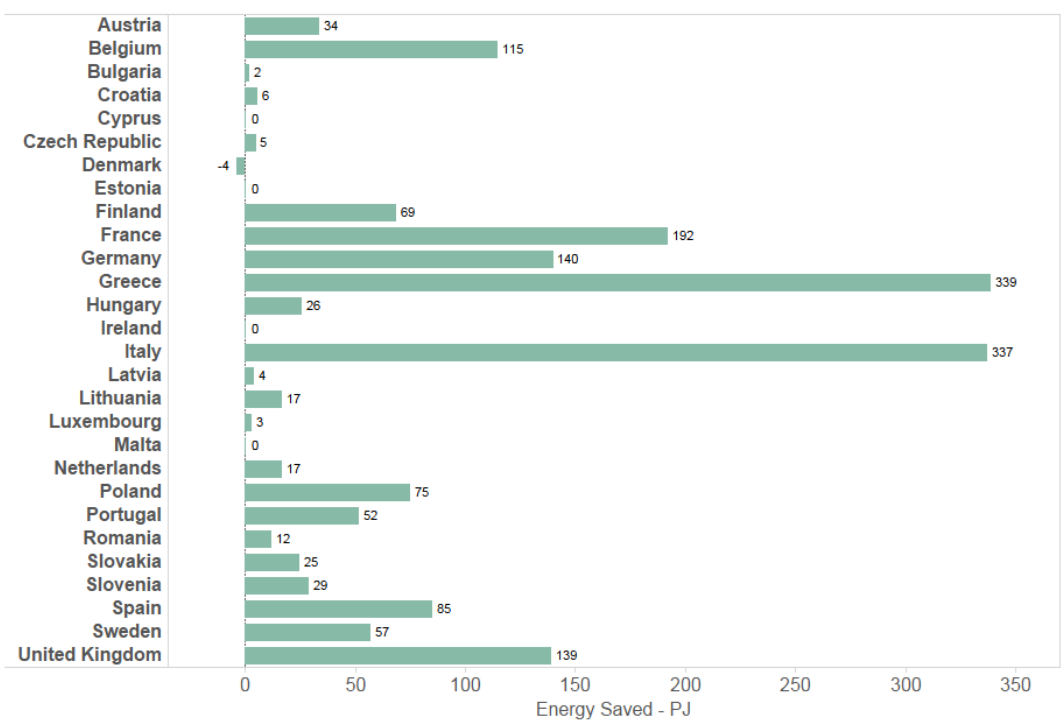


Figure 27 EU 28 - the embodied quantity of EC thermal energy required for extraction related to imported Gas and Oil saved to the country because of imports (PJ, 2013)

Having calculated this quantity of embodied "virtual" consumption of thermal energy carriers we can also calculate the relative quantity of CO_2 emissions (the arrow with the label G in Figure 22). This assessment is illustrated in Figure 27.

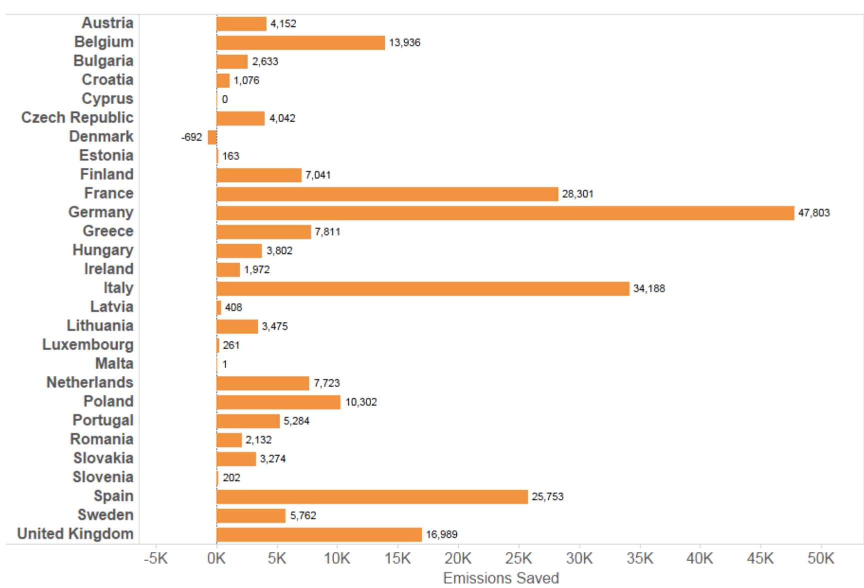


Figure 28 EU-28 – the externalized CO2 emissions referring to the energy used for extraction of the imported oil and gas (in million kg of CO2, in 2013)

In the same way, we can assess the labor embodied in the extracted oil and gas imported by EU countries. That is also labor input - another factor of production (fund element) key for the operation of processors- is saved because of the externalization provided by imports. This assessment of required amount of labor refers to the arrow with the label A in Figure 22.

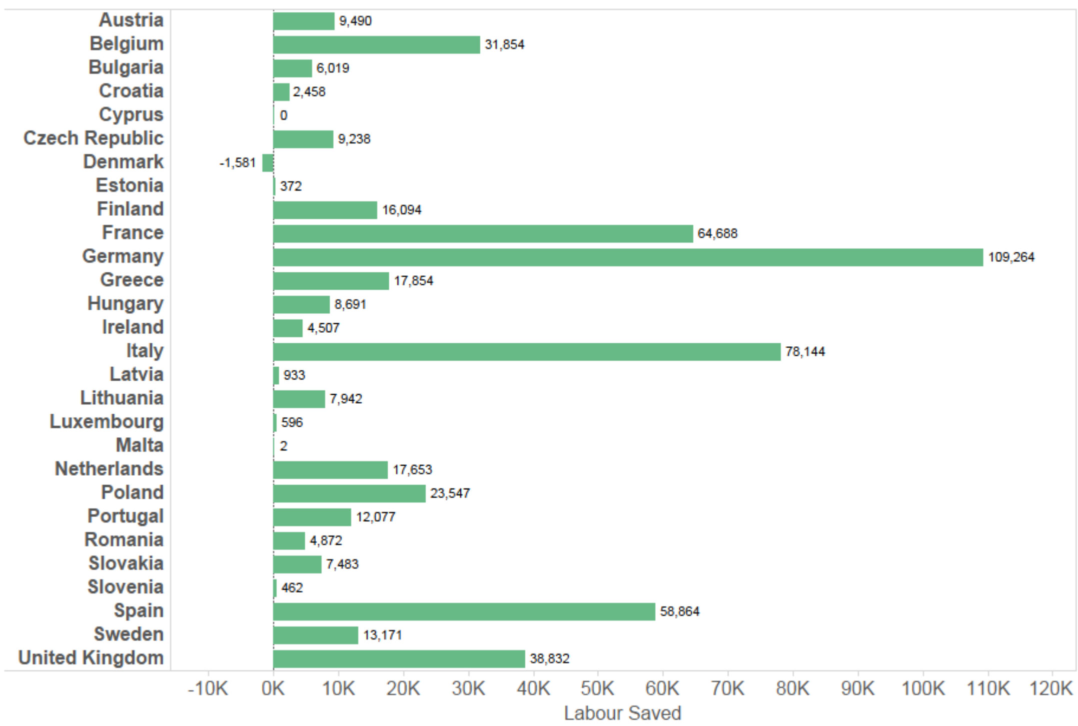


Figure 29 EU 28 - externalized labor requirement in extraction through imports of oil and gas (2013, measured in thousand workers)

An assessment of the amount of labor required for the activity of extraction and that is externalized because of the imports of oil and gas is illustrated in Figure 29, it refers to the year 2013 and it is measured in thousand workers.

So far so good, assuming that the data used for this assessment were reliable it would be possible to estimate (with some approximation) the effects of the externalization represented by imports in terms of internal inputs saved (fund and flow elements on the top of the processor) and the external flows externalized (the requirement of PES on the supply side, the environmental loading of the emissions on the sink side). However, as discussed in section 2.7.3 there are reasons to doubt of the robustness of these assessments. Especially at the beginning of the sequential pathway, when extracting Primary Energy Sources, the accounting of the actual quantities consumed gets muddled by the blurring of the division of this category of accounting: at time crude oil (PES) is used to generate locally the electricity (EC) used in the process of extraction and this self-production and self-consumption of energy at the local level is not recorded in the official statistics . . .

2.7.2 Individual task: Refining

Here we repeat the analysis of the effect of externalization due to imports in relation to another functional activity/processor defined in the sequential pathway of production of liquid fuel (Figure 21): *refining*. As done with the analysis of extraction we start by considering the quantities of domestic refining illustrated in Figure 30.

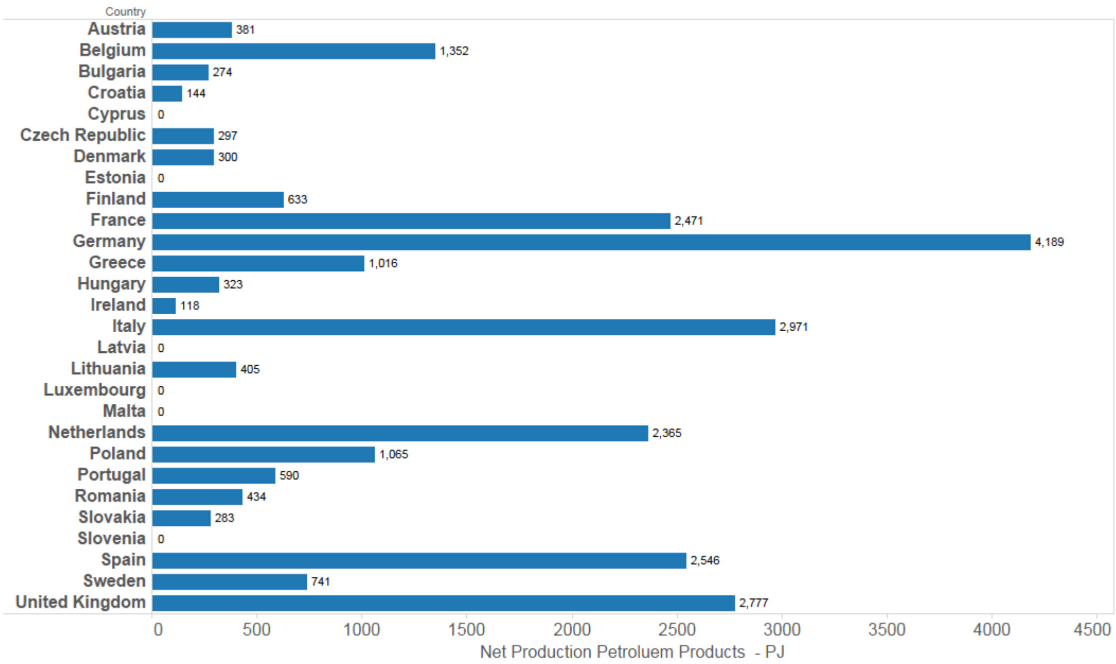


Figure 30 EU 28 – Production of oil products via refining by country (2013 in PJ)

Then we calculate the emissions for the domestic refining, from the consumption of fossil energy in this activity (in million kg of CO_2). This is illustrated in Figure 31.

However, when coming to the analysis of the import/export of oil products (the quantity of EC liquid products produced by this energy system) we face another problem. In fact, the energy sectors of modern countries are quite open in terms of traded flows, so we can have a situation in which the energy system in charge for producing energy carriers – in this example oil products - is exporting and importing them simultaneously. In this situation, in order to identify the relevant factors to be considered to study energy efficiency, we have to carry out a careful analysis of the set of transformations. In this situation, some of the conversions of energy taking place in the energy sector are relevant for an assessment of energy efficiency – i.e. the conversions referring to the energy carriers that will be used by the rest of the society. Other conversions, those referring to energy carriers that will be exported (and used elsewhere) are only relevant for economic reasons. For example, oil exporting countries consume a lot of energy carriers in extracting and refining energy carriers, while depleting their reserves of oil, but they do so not for energetic reasons! Oil producing countries will not metabolize all the oil and oil products they produce!

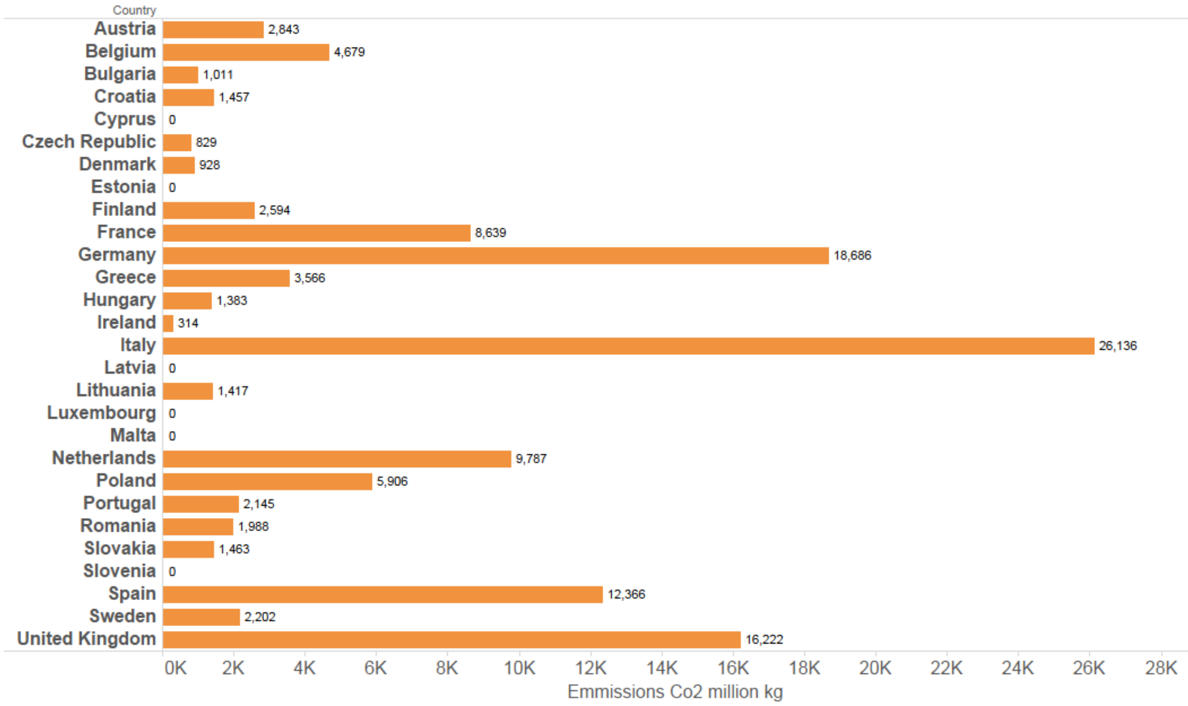


Figure 31 EU 28 – emissions of CO2 reflecting the consumption of fossil energy in domestic refining (2013, million kg of CO2)

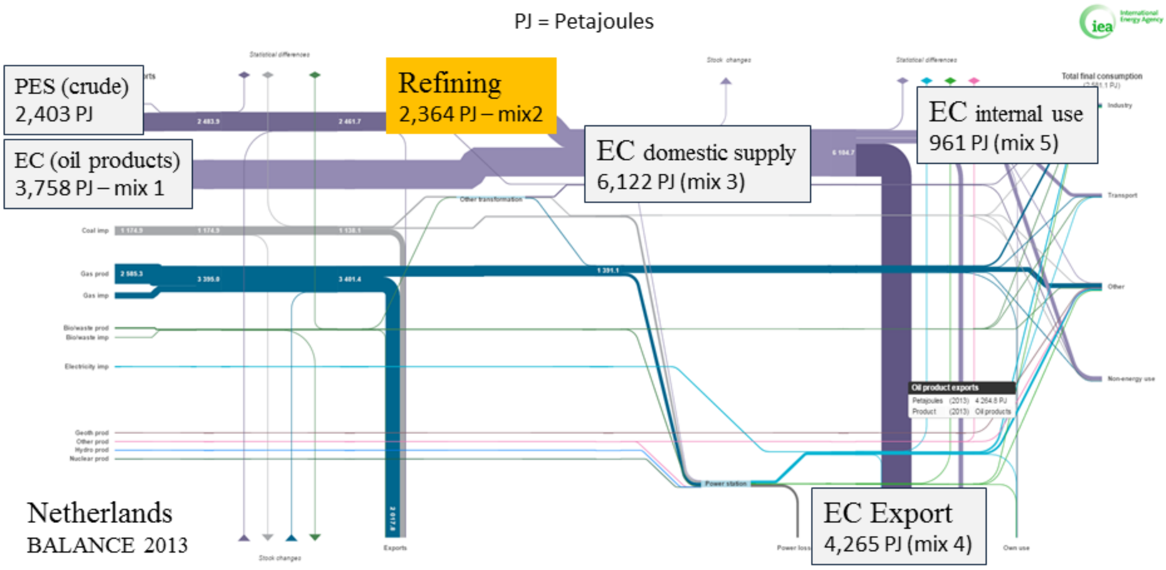


Figure 32 The energy Balance (2013) of the Netherlands using Sankey diagrams (IEA)

The energy balance, illustrated in Figure 32 of the gas and oil system of the Netherlands shows that the energy sector of the Netherlands is exporting more EC that it produces. When considering the sum of the imported EC (3,758 PJ) and the domestically produced (2,364 PJ) energy carriers against the quantity of EC domestically consumed (961 PJ) we can conclude that the production of EC in the Netherlands is heavily driven by economic considerations: not only NL produces EC but also it imports EC to process and re-export them. This fact implies that the mix of: (i) EC imported (mix 1); (ii) EC produced in the local refining process (mix 2); (iii) EC domestically used (mix 5); and (iv) EC exported (mix

4) are different. Not all the power capacity of refining of the Netherlands is used to generate the type of input of energy carriers used by that country. For this reason, it if we calculate the benchmark for the processor “domestic refining” – the requirement of labor, fuels, thermal and electricity inputs per PJ of EC produced – based on the statistical records of the inputs getting into it, it is very likely that the resulting processor will refer to a mix of production of oil products which is different from the one consumed in the Netherlands.

It should be noted that this is just one of the many problems faced when trying to characterize output/input benchmarks in order to calculate “virtual” consumptions or “embodied” quantities in inputs used by a system and produced elsewhere. This common epistemological problem faced in Energetics and Life Cycle Assessment is illustrated in Figure 33.

The phenomenon illustrated in Figure 33 refers to the concept of network niche associated with the existence of established metabolic networks – e.g. the niche of a herbivores within the food web of an ecosystem. The example given in Figure 33 is easier to understand because it is related to a metabolic network easier to understand: the circulatory system of a human body. The set of veins and arteries going from and to the different organs of a human being defines a “network niche” for the functional type – human heart. That is, the organization and the functioning of the human body (the metabolic network) representing the metabolic context of a human heart define a set of expected characteristics of the human heart, which are independent from the specific instance of heart that will be inserted in the niche. That is, the human heart must: (i) metabolize a given profile of inputs (venous blood) and outputs (arteries blood) per unit of throughput processed (the pace of pumping) – it must fit the metabolic niche; and (ii) have a size compatible with the size of the rest of the network - it must fit in the spatial niche. This definition of the processor obtained looking at the external view of the functional elements can be described using statistical data: i.e. by measuring the flows getting in and out, the size and then by calculating the profile of benchmarks. This is what has been done so far in section 2.7.2 for the analysis of oil and gas extraction, when using “virtual” and “embodied” quantities that would have been required to produce the imported oil. However, the characteristics of a human heart can also be determined when looking at its structural organization, reflecting its process of production – the blueprint used to make it. This implies a bifurcation of the possible definition of the metabolic characteristics of elements of metabolic networks: (i) they can be defined by the mutual information stored in the network outside the node – the definition of a network niche; and (ii) they can be defined by the direct information used in the blueprint for their construction. This bifurcation flags the existence of an epistemological fragility in the analysis of metabolic elements. The coexistence of an identity defined by the existence of a network niche and an identity defined by a blueprint can imply degeneracy in the mapping of functional type onto structural types. For example, Figure 33 shows that two different structural types – a natural heart and an artificial heart - can express the same functional type.

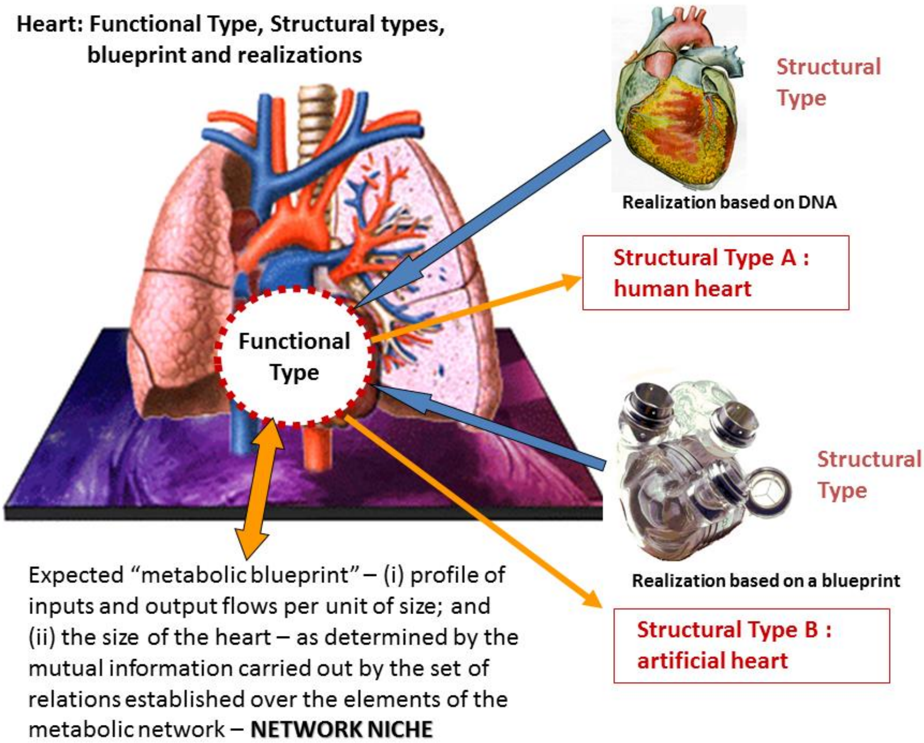


Figure 33 The complex nature of the relation between functional and structural types and between templates and realizations (after Giampietro 2003)

By adopting a relational analysis of the metabolic patterns it becomes possible to clarify the nature of this problem and, to a certain extent, handle it. In fact, when considering the special structure of complex metabolic systems we can use a series of concepts derived from hierarchy theory, and theoretical ecology (Allen and Starr, 1982; Giampietro et al. 2006; Giampietro et al. 2012; Ulanowicz, 1986) helping in understand the nature of the challenge of quantification.

The example of the network niche (functional type) mapping onto two distinct structural types is very relevant for energy analysis. In fact, the case presented earlier – in Figure 16 of the coexistence of different technological solutions used in the Oil and Gas sector of Brazil to express the same functional process. As illustrated in Figure 16 when determining the characteristics of the functional processor "extraction" we have to consider the characteristics of at least two structural types – offshore and onshore drilling. In the same way, when determining the characteristics of the functional processor "refinery" we have to consider the characteristics of at least three structural types – large, medium, small refinery. This implies that not only we have to know the specific technical characteristics of these types, but also their relative size (role that they play) in the functional processor. For example, in Figure 16 off-shore extraction represents 90% of the processor, whereas on-shore extracts only 10% of the total. In order to express the characteristics of the functional processor we have to "scale" the information referring to the different structural types according to their relative importance in expressing the function. The same type of scaling is required for the information referring to the metabolic blueprint of small, medium and large refineries processing respectively: 15%, 64% and 21% of the total supply – Figure 16.

2.7.3 Lessons learned from these examples

After having presented these examples we can get back to the three goals of this section. The examples confirm the first of the three points: (1) it is possible to analyze the effect of externalization associated with imports in the energy sector. However, these examples also show a systemic problem faced when trying to use available statistical data. This is an issue referring to the other two points: (2) this analysis cannot be done using only data taken by energy statistics; and (3) statistical data require a satellite accounting integrating other sources of information in a relational analysis of the energy sector. This satellite accounting should consider the characteristics of fund elements (e.g. power capacity and infrastructures), rather than only flow elements (the existing statistics focusing only on quantities of energy flowing). This will help also to individuate better categories of accounting for the flows.

For example, we can go back to the analysis of the process of domestic extraction of oil and gas presented in Section 2.7.1. Using the data set used for the analysis we can calculate the EROI (Energy Return On the Investment) – that is the output of energy carriers divided by the input of energy carriers used for the extraction – for extraction in the different countries. However, the values found in this way are not consistent with the expected benchmarks of this process. The data used in our analysis indicate a value of 137/1 in Bulgaria, 50/1 in Germany, 50/1 in the Netherlands, 20/1 in Romania. In the field of energetics the EROI of the process of extraction of the oil and gas industry is a well-known indicator. An example of the historic values of this indicator in the USA is provided in Figure 34.

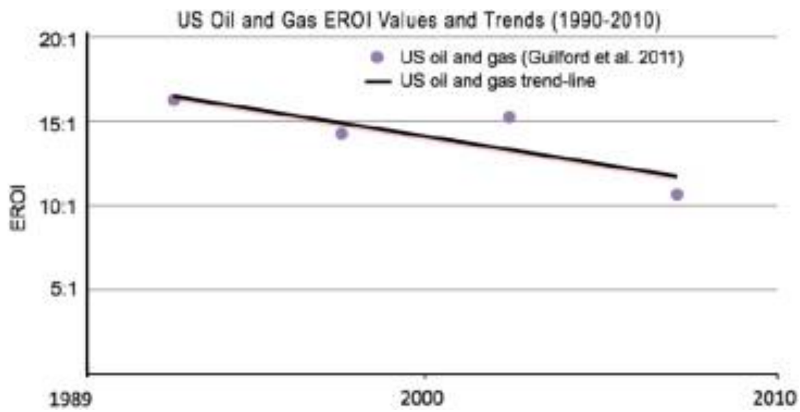


Figure 34 The EROI of "Oil and Gas Discovery and Production" in the USA – 1910-2010 (Guilford et al. 2011)

Also in this example, we find the problem is generated by the choice of category used in statistics. The extraction of natural gas has a much higher EROI (e.g. around 50/1) than oil (in between 20/1 and 10/1) so that the value of the EROI for the category "gas and oil extraction" really depends on the relative mix of the two forms of energy in the output. Additional information would be useful to clarify the issue. After providing an assessment of the relative importance of gas and oil we could identify as "unreliable" statistical data those generating values of output/input higher than 70/1. A second important quality check should be related to the use of fossil energy PES in-situ for powering the activities of extraction via a self-production and consumption of EC. When energy carriers are produced and consumed in loco they do not pass through the market. For this reason they may or may not be recorded in statistics. In the second case, we obtain records of EROI much higher than those obtained when studying the technical coefficients describing the performance of the local plants.

In conclusion we can say that: (i) the example shown in Figure 32 shows the impossibility of characterizing the processor producing the EC consumed by the Netherlands using the information provided by Sankey diagrams; (ii) the example shown in Figure 33 (in relation to the analysis given in Figure 16) shows the impossibility to have an unambiguous mapping when considering processors referring to functional and structural types; (iii) the example shown in Figure 34 questions the reliability of assessments based only on statistical records about energy flows, when flows are aggregated without considering the existence of relevant differences. Energy flows can be difficult to categorize, individuate and track inside the mess of energy transformations taking place in the energy sector. These examples suggest that a more robust quantitative analysis is needed. In order to understand the functioning of an energy system it is essential to combine together top-down information gathered from statistics and bottom-up information gathered from the existing knowledge of technical coefficients referring to fund elements used in processors. However, above all it is necessary to have a pre-analytical choice of a taxonomy of categories to be used for the accounting. This different approach to energy accounting would require embracing complexity and acknowledging the fact that quantitative energy analysis based on reductionism cannot generate quantitative information useful for policy.

2.8 Developing quantitative analysis based on assessment of Power Capacity

Contrary to what used to be in pre-industrial times, when slaves and animal power where the most important forms of power capacity, technical conversions dominate the transformations of energy forms in the energy sectors of modern societies. In modern energy sectors, the role of the fund element *Human Activity* (labor) - even if still a necessary input to the processors – has been dramatically reduced. Only 0.1% of all of the total human activity expressed in a modern society (less than 1/1,000!) is invested as paid work in the energy sector (Giampietro et al. 2012). This means that less than 10 hours of work per year per capita in the energy sector are enough to guarantee the supply of the energy consumed by the whole society per capita in a year (directly and indirectly by the rest of the economy).

This assessment points at the tremendous importance of heavy investments of power capacity – technical capital – in the energy sector. Human activity provides just an input of information/control to the power capacity expressed by technology. Hence, when looking at production side (the transformation taking place in the energy sector) “power capacity” is the key fund element to be considered. However, in order to characterize the features of power capacity that affect the technological performance of the energy sector it is important first of all to identify “typologies of processors” the use this power capacity to express functions.

Table 3. An example of analysis of the energy sector by typologies of power capacity

FUEL TYPE	Sum of CapacityMW	Sum of NumberOfPlants
Biogas	1	134
Biomass	3,298	128
Blast_Furnace_Gas	92	2
Brown_Coal	30,815	36
Coal	60,639	115
Coke_Oven_Gas	860	3
Diesel_Oil	2,260	37
Fuel_Oil	18,159	36
Gasoil	425	3
Geothermal	873	22
Hard_Coal	46,955	94
Heavy_Fuel_Oil	8,164	18
Hydro	63,926	2500
Landfill_Gas	18	377
Lignite		1
Munic_Solid_Waste	1,885	181
Naphtha	17	5
Natural_Gas	133,526	612
Nuclear	108,759	71
Oil		1
Peat	404	5
Refus_Derived_Fuel	19	1
Residual_Fuel_Oil	512	4
Solar_Radiation	1,407	374
Tidal	638	5
Waste_Heat		1
Wave	18	5
Wind	24,709	2388
Grand Total	**508,379**	**7159**

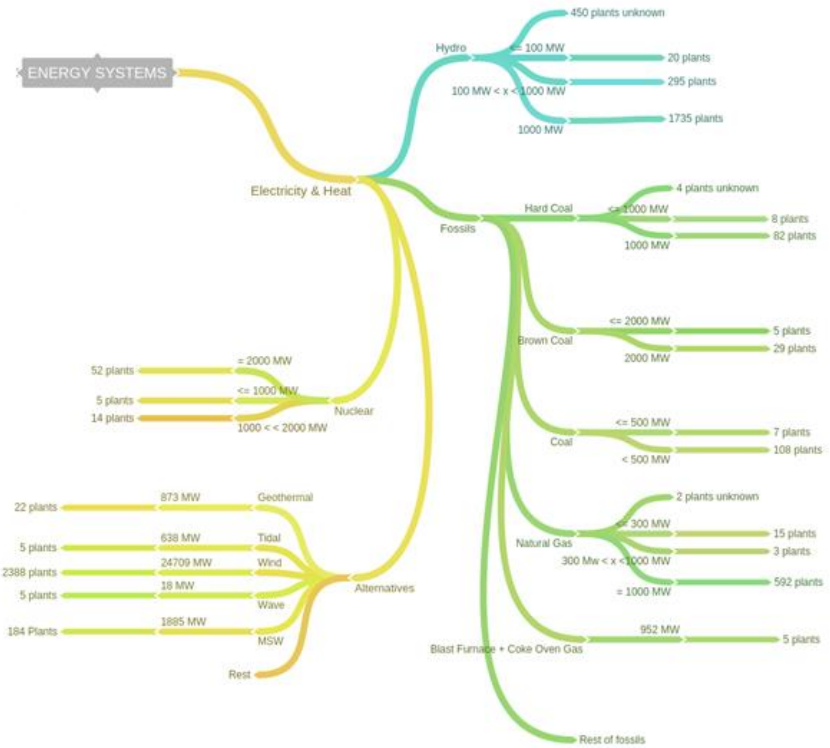


Figure 35 Example of categorization of instances of power capacity (number of plants)

An analysis focusing on power capacity requires a pre-analytical discussion and an agreement among the analysts on a lexicon of typologies of power capacity. In turn, this requires defining useful criteria for aggregating the different structural elements operating in the energy sector in "equivalence classes" – homogeneous typologies – when analyzing their specific functions in the expression of the metabolic pattern of the *supply side*. An example of how to organize this pre-analytical decision is given in Figure 35.

After having selected a taxonomy of types of power capacity – the type of fund element used in the processors – it becomes possible to analyze and measure the number of structural elements associated with the operations of the various processors and their size. The example of characterization of the power capacity using typologies given in Table 3 is based on data from *Enipedia* - an extensive, up-to-date, collaborative effort that serves both as a database and a wiki - bringing together data and information on all the world's power plants.

A proper organization of the accounting of power capacity over useful categories (reflecting the individuation of functional typologies) is essential to be able to individuate the features of the different types of power capacity affecting the performance of the energy sector. For example, let's consider the characterization of the different typologies of power capacity used in EU 28 provided in Tab. 4.

Table 4. Describing the characteristics of different typologies of power capacity used in EU 28 to generate electricity

EUROPEAN UNION 28			Power Capacity	% of total Installed Power Capacity	Generation	% of total Production	Count of Number Of Plants	Capacity Load
		PES type	MW	%	Gwh	%	#	Gwh/MW
GENERATION OF ELECTRICITY	Nuclear	Nuclear	108,759	21%	947,207	33%	71	8.7
	Fossil	Brown Coal	30,815	6%	239,959	8%	36	7.8
		Coal	60,639	12%	388,964	14%	115	6.4
		Hard Coal	46,955	9%	281,341	10%	94	6.0
		Gas[1]	134,478	26%	499,557	18%	617	3.7
		Fuel [2]	29,556	6%	98,185	3%	105	3.3
	Alternative	Mix[3]	33,251	7%	138,670	5%	3,620	4.2
	Hydro	Hydro	63,926	13%	240,574	8%	2,500	3.8

1. Natural Gas + Blast Furnace Gas + Coke Oven Gas
2. Fuel Oil + Diesel Oil + Gas-Oil +Residuals Heavy Fuel Oil + Naphtha + Oil + Refuse Derived Oil + Residual fuel oil
3. Wind + Wave + Tidal + Solar + Geothermal + Landfill Gas + MSW + Waste heat + Biogas + Biomass

In Tab. 4 we get information about: (i) the relative importance of the different typologies of power capacity in determining the overall supply of electricity (based on quantity measured in GWh); and (ii) the relative size – measured in MW (a factor that can be associated with an economic analysis of the cost of the supply) – of the power capacity; and (iii) the load capacity – the ratio of the electricity produced in a year per unit of power capacity. When looking at this last indicator we can discover important differences among the different typologies of plants. There are some typologies of Power Capacity that have a high ratio GWh/MW while other typologies have a much lower value. In relation to the usefulness of this indicator, we can recall here the wisdom of Carnot mentioned in the introductory section of this deliverable. In general, a low utilization of power capacity is considered to be a “bad” performance for power capacity. A low GWh/MW ratio implies that the GWh actually produced are less than the GWh that could have been produced if the power capacity would have been used more during the year. However, we have to understand that different typologies of power capacity do express different functions in the energy sector. This understanding can reverse such a judgment. For example, from Table 4 we see that fossil fuel powered plants running on gas and fuels have a much lower capacity load than the ones running on coal. However, this characteristic does not depend on either bad quality of the energy input or bad technology. Rather this difference depends on the different role that these plants play in the supply of electricity. A large fraction of the plants running on gas and fuels belong to the category of “peakers”. They have a low utilization factor, because they are switched on only in moments of very high demand. That is, their function is not to provide the baseload of electricity supply to society, but rather they have the function of handling the peaks of demand (this is what justifies their name). The question then becomes: “is it efficient to invest MW of power capacity in a power plant that will be used only a limited number of hours in a year”? Then the answer is YES, if this solution avoids to keep switched on a surplus of power capacity – used for the base load supply - for many more hours in a year, generating electricity that cannot be used, in order to be able to cope with peaks when they will occur. As a matter of fact, this is a problem faced now in Germany with the Energiewende, where coal fired plant are kept switched on (even if they do not supply electricity) as potential back-up of renewable sources of electricity.

The low utilization factor of power capacity associated with wind and photovoltaic has a complete different explanation. There the problem is generated by the unpredictability of climatic conditions. The problematic utilization of the power capacity of renewables is made worse by the fact, that in the metabolic pattern of developed countries the pattern of electricity consumption – the expectations of the consuming side of the metabolic pattern – has to be matched “no matter what”. It requires back-up of power capacity 24 hours a day 365 day per year. That is, within the existing pattern of production and consumption of electricity, not only the alternative sources require much more power capacity for supplying the same quantity of electricity (because of their intrinsic low utilization factor), but also they require an extra quantity of power capacity (that will also be used at a low level of power capacity) as a back-up. However, it should be noted that this problem is not due to bad characteristics of alternative energy sources, but to an unwise strategy attempting to couple a supply side based on alternative energy to a consumption side that has evolved to consume as much as possible fossil energy – a demand of electricity to be matched “no matter what” (for more on this see Giampietro et al. 2013).

A last observation is due on the values of capacity load reported in Table 4. When these values are checked against the benchmarks of the different typologies of power capacity derived from other sources, they seems to be quite high. Probably the assessments of the MW of the different types of power capacity found on Enipedia are underestimated or estimated using particular criteria not coinciding with the criteria used to define the standard benchmarks. This example flags again the need of having an agreement on how to integrate the information coming from different sources in order to generate more robust assessments and to make transparent under which assumptions the various quantitative assessment have been generated.

2.9 Power capacity and path dependence (carbon lock-in)

When looking at the existing profile of power capacity in the processors dedicate to the production of energy carriers we can clearly see that the technology of the Energy Sector is still based on conventional technological solution organized over a centralized energy system generating economies of scales. Unfortunately, as indicated by Sovacool (2016), a conventional organization of the energy sector based on centralized energy systems and economies of scale requires huge investments which in turn necessitate longer periods of pay-back. This solution generates a strong path dependence/lock-in.

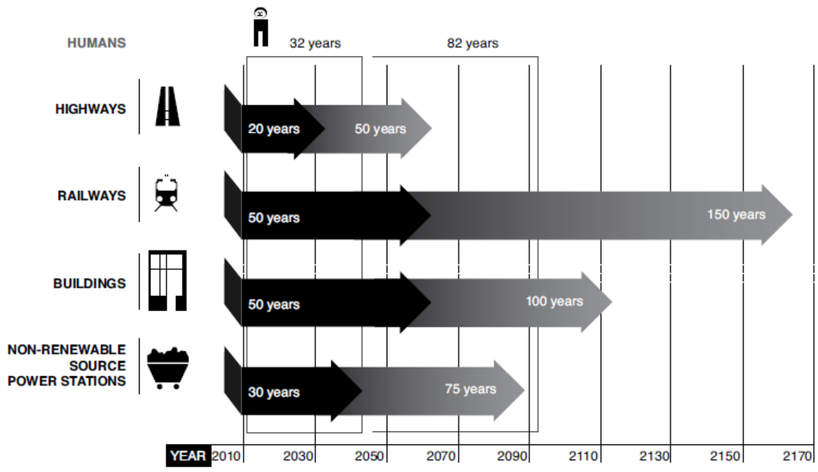


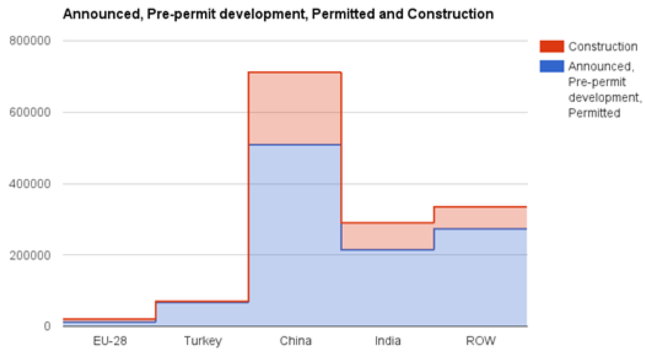
Figure 36 Expected lifespans of some energy technologies

Path dependence is determined by a set of constraints associated with decisions made in the past rather than by the options given by current conditions. In this case, the path dependence on the carbon economy is determined by: (i) the large investments required to achieve economies of scale in the exploitation of non-renewable forms of energy production (nuclear and fossil energy) require the adoption of plants having a life span of between 30-75 year – see Figure 36; (ii) the stable definition of a pattern of supply of energy carriers locks-in the resulting pattern of end uses (the nature of the processors used to convert the energy carriers into useful tasks).

Also in this case, very expensive infrastructures – e.g. highways, pipelines, railroads, airports – and resilient classes of prime movers and energy converters – e.g. the engines of cars, ships, machineries, airplanes, appliances - tend to create a blockade in the system, leaving very little room for maneuvering and transitioning into alternative form of energy production and consumption.

As Erickson (2015) puts it: *"once certain carbon-intensive development pathways are chosen and capital-intensive investments are made, fossil fuel dependence and the carbon emissions that come with it can become 'locked in', making a transition to lower-carbon development pathways difficult and increasing the risk of exceeding climate limits".*

For example, only within the period of 2010-2015, a power capacity of 464,840 MW coal plants have been installed globally.[5] – Figure 37.



	Rest of World	EU – 28	Turkey	India	China
Announced + Pre-permit + Permitted	1,075,171 MW	11,816 MW	66,989 MW	214,469 MW	508,914 MW
Construction	351,661 MW	8,655 MW	2,965 MW	75,665 MW	202,899 MW

Figure 37 An analysis of the situation in relation to the creation of new fund elements (power capacity) related to processors of fossil energy

Looking at Figure 37 we can see that even within the EU-28 there are plans (announcement, release of pre-permits and construction of) for future investments in new coal power plants.

In relation to the analysis provided in Section 1 we can observe that policies should not be based on analysis and targets based on the accounting of flows of "primary energy" and "final energy consumption". In the energy sector of modern economies energy flows are difficult to define and even more difficult to assess. For this reason it would be much more effective to: (i) track the investments in fund elements within the energy sector; and (ii) regulate and measure the energy imports. Energy policies should prevent the creation of further lock in into conventional fossil based system for the upcoming years.

However, the formulation of these policies should be based on a very careful assessment of the feasibility, viability and desirability of these policies – that is, one should have a quite robust approach to check how the performance of the economy will be affected by a dramatic reduction in the use of fossil energy. An African proverb states that "*A fish is the last to acknowledge the existence of water".* Western societies are so used to the energetic bonanza provided by fossil energy that it seems that they cannot see how much their life depends on it. Many recipes for a quick decarbonization of the economy

[5] Summary: http://endcoal.org/wp-content/uploads/2016/01/Global-Coal-Plant-Tracker-December-2015-Summary-comparison-2015-2016-New.pdf

that are supposed to preserve its current performance and material standard of living seem to be based on a clear underestimation of the key role that fossil energy plays in supporting modern life styles.

So, if we want to visualize the effect of scenarios of decarbonization policies, we should first of all start by defining the required changes in the size and quality of fund elements to adjust the different flows required by the decarbonized metabolic pattern. As discussed earlier power capacities can be easily labelled by type and size. Then after having framed the set of energy transformations taking place in a society in terms of the characteristics of the processors required for them, it becomes easier to track the resulting flow elements identifying in this way the technical aspects related to efficiency of the relative conversions.

This type of analysis of the processes used to generate Energy Carriers can be easily applied to both petroleum products and/or electricity. Then one can study what type of replacement of power capacity would be needed (and the relative processors) to stabilize the same flows consumed by society, or how to adjust the flows to a different type of metabolism. By integrating the analysis of the metabolic pattern in relation to conversions based on flow-fund benchmarks (on the supply side), imports/exports (in relation to the level of openness of the system) and again on flow-fund benchmarks (on the consumption side) it becomes easier to have a more holistic picture of the state of the art and the possible effects of policies.

Remaining into the example of the analysis of expected changes in the power capacity related to coal conversions, the global coal plant tracker summary illustrated in Figure 38 illustrates the details of the status of new power capacity instalments for coal power plants as seen for the EU 28. Although, 33% of the coal power capacity has been shelved, an almost equivalent quantity - 30% of total - has started new operations, while 15% are in construction and 22% are under way for development. Considering the lock-in associated with the establishment of new power capacity, that has to be used as much as possible in order to pay back the economic investment, we can calculate the quantity of primary energy, secondary energy (electricity) and emissions that these investments in power capacity do imply in the future.

Building a characterization of the network of energy transformations taking place in the energy sector of EU countries, in which the assessment of the various flows can be: (i) predicted from the characteristics of the processors and the metabolic network in which they are operating; and (ii) confirmed by statistical data; would imply two major achievements:

(1) a more robust understanding and characterization of the processes taking place in the energy sector in terms of quantitative representation; and

(2) the possibility to run simulations capable of checking the feasibility (compatibility with processes outside human control), viability (compatibility with processes under human control) and desirability (compatibility with the aspirations and normative value of the society).

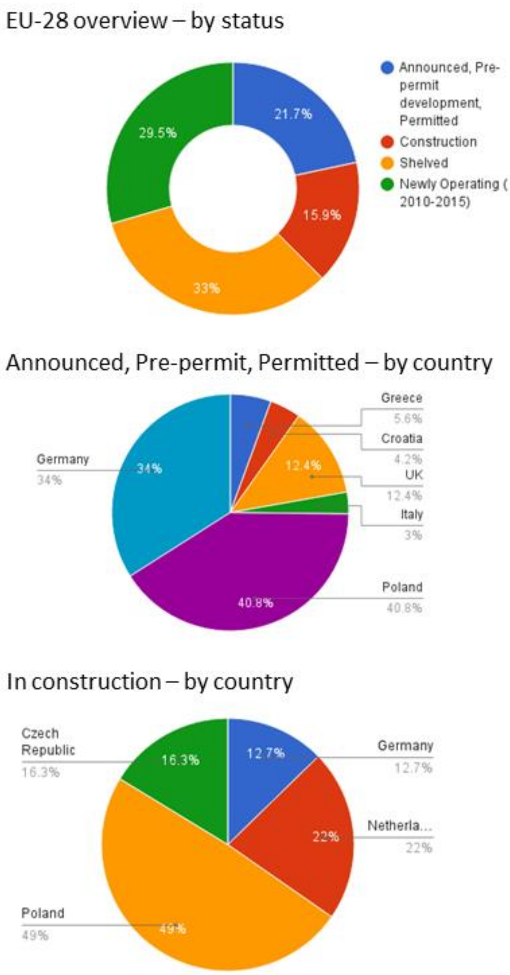


Figure 38 An overview of constructed or forthcoming (Announced, Pre-permitted for Development and Permitted) coal plants for the EU28 - http://endcoal.org/global-coal-plant-tracker/

2.10 The urgent need of a quality check on the quantitative information used to study the performance of the energy sector

A successful energy transition away from fossil energy will require a massive structural change in the metabolic pattern of society that, in turn, will imply a radical change in the pattern of production and consumption of energy carriers. Put in another way, a successful energy transition away from fossil energy will require a clear discontinuity in the quantity and quality of technology used in the energy sector. This clear discontinuity will have to be reflected not only in the different quantity and mix of energy carriers, but also in the way energy carriers are used. A significant change in how to produce and consume energy carriers will require, obviously, a significant change in the quantity and quality of structural elements - the fund elements operating in the processors expressing end-uses – used in the society. For this reason, the discussion of energy policies aimed at generating a change in the actual metabolic pattern of energy within the EU cannot be based on an analysis of energy transformations focusing only on the accounting of flows – i.e. by establishing targets of reduction of flows (reduction of 40% of primary or final consumption by the year 2040); or by improving the existing ratios over flows (reduction of the actual level of energy intensity or carbon intensity); or by improving the specific technical coefficients describing a local task assessed at the micro-scale (increasing the mileage of a car, reducing the heat loss of the window).Such a discussion has to address the implications of a massive substitution of the power capacity required, both in production and consumption, to consume in different way different mix of energy carriers used to express different end uses.

Therefore, an informed discussion about energy policy aimed at an energy transition away from fossil energy (low carbon economy) and at increasing the sustainability of the metabolic pattern of modern society needs a holistic understanding of the relations between:

(1) the quantity and quality of fund elements used to produce energy carriers in the energy sector. It is the combination of the quality (the lexicon of typologies of power capacity found in the different processors operating in the different energy systems) and the quantity of power capacity used for each type of processor, that defines flows of required Primary Energy Sources (from nature) and the supply (flows) of Energy Carriers (to the rest of society);

(2) the quantity and quality of fund elements used to consume energy carriers in the rest of the economy. It is the combination of the quality (the lexicon of typologies of power capacity found in the different processors operating in the various components of the society) and the quantity of power capacity used for each type of processor, that defines the functions expressed by the society and the relative flows of Energy Carriers required for expressing them.

As discussed in Section 1 we can look at the metabolic pattern of energy of a society from two sides:

*** the production side (referring to the activities taking place in the energy sector gathering and transforming PES into EC).** The Energy Sector includes the mix of Energy Systems in charge of: (i) the supply of energy carriers through the extraction/exploitation of PES and their transformation into EC; and (ii) the distribution of energy carriers to the final users.

* **the consumption side (referring to the various uses of EC within the society) –** the profile of End Uses of energy carriers needed to express the functions associated with the reproduction of the socio-economic process defines: (i) what is required as supply from the energy sector; (ii) what are the functions expressed by the society to maintain its identity.

The metabolic pattern of energy in a society requires establishing an impredicative relation between these two sides: (i) the production side *is expected to supply* a given quantity and mix of energy carriers reflecting the requirement of the consumption side; at the same time (ii) the consumption side *can only consume* a given quantity and mix of energy carriers according to the supply made available by the production side. This implies that, the characteristics of each one of the two sides affect the characteristics of the other.

Because of this impredicative relation, what is produced and what is consumed in a society in terms of quantity and mix of energy carriers depends on a dynamic equilibrium between demand and supply determined by the different relations between "investments" and "returns" of energy carriers associated with the activities expressed by the two sides. ***This is what makes the use of the concept of efficiency unpractical***. It is simply not possible to adopt a substantive definition of an "input" and a resulting definition of the "result obtained using that input" that can be used to quantify the efficiency of the process – i.e. to assess either how one can obtain the same result with less input or how one can get a better result with less input. The two side of the dynamic equilibrium always re-adjust simultaneously to changes!

The *supply side* (the energy sector) expresses activities that consume energy carriers. However, these activities imply a production of energy carriers which is larger than the consumption – a net supply for the rest of the society. The *consumption side* (the rest of the society) expresses activities that only consume energy carriers without generating energy carriers. The consumption side, even if not generating any net supply of energy carriers, generates other key inputs required for the reproduction of the society and for the proper operation of the energy sector. The consumption side: (i) generates food (in the agricultural sector); (ii) gathers minerals (in the mining sector); (iii) produces products and technology (in the industrial sector); (iv) reproduces human activity (in the household sector); and (v) reproduces institutions (in the service sector). The sectors belonging to the *consumption side* need the supply of energy carriers – a supply of exosomatic energy* [= energy transformations taking place outside the human body but under human control] – for expressing their functions. In the same way the energy sector – the *supply side* - needs inputs from the *consumption side* for its operations.

Understanding the nature of this impredicative relation over the characteristics of the "production side" and the "consumption side" requires considering the different factors determining the feasibility, viability and desirability of the dynamic equilibrium.

As discussed in Section 1 they are: (i) the quality, quantity and mix of PES; (ii) the quality, quantity and mix of EC required by the mix of end uses; (iii) the effect of the import/export.

As discussed in Section 2, these factors can be studied by analyzing the metabolic pattern of society across different scales. However, this analysis requires the integration of information coming from statistical sources and by the analysis of technical coefficients across different scales.

In order to carry out a diagnosis capable of answering all these questions we have to bridge in a common analysis the two sides of the metabolic pattern: production and consumption – and this is made possible by the adoption of the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)[6] framework.

A better understanding of the metabolic pattern is essential in order to have an informed discussion over policies aimed at increasing energy efficiency. More specifically there are key questions that have to be addressed in order to have better informed decisions about effective energy policies aimed at generating an energy transition toward a low carbon economy:

(i) how would the metabolic pattern of energy of modern societies look if fossil energy would be totally phased out?

[6] For an extensive overview of applied cases see: https://en.wikipedia.org/wiki/MuSIASEM

(ii) how much can we reduce the end uses in the consumption side without affecting seriously the viability of the economic process and the desirability of the standard of living?

(iii) what are the factors that generate a lock-in the existing metabolic pattern based on fossil energy?

(iv) how serious is the dependence of modern societies on import of fossil energy?

Right now in the EU 28 many research resources are used for generating complicated models, based on the philosophy of reductionism, mixing together economic and biophysical variables and having the goal to indicate “optimal solutions” for achieving a maximum in “energy efficiency”. According to what presented in this deliverable it would be wise to allocate at least a small fraction of these resources for implementing alternative approaches addressing the complexity of the metabolic pattern of energy in a different way. An energy transitions to a low carbon economy would require an unthinkable revolution in the way future societies will carry out their activities. Nobody can predict, with models based on reductionism, true novelties – what is called in complexity jargon “the emergence of new features and meanings”.

Conventional models in this field can only generate four standard scenarios: (i) business as usual; (ii) more of the same; (iii) less of the same; and (iv) the achievement of the targets determined by the funding agency through a series of “rosy assumptions” difficult to believe.

This last solution translates into a stabilized use of conventional models used under the modality (iv) to define targets and directives based on wishful thinking. These targets and directives are becoming more and more difficult not only to achieve but also to defend in terms of their credibility.

With this deliverable propose an alternative approach to the energy analysis of the economic process that is based on relational analysis and complex system thinking: Multi-Scale Integrated Assessment of Societal and Ecological Metabolism (MuSIASEM). This approach has the potentiality of overcoming a few of the epistemological problems faced when trying to analyze complex process using reductionism.

WRAP UP

Discussion of the limits of the proposed approach

The proposed approach of accounting (MuSIASEM) has been developed according to the rationale of complexity theory: an "object" is complex when its representation cannot be compressed without losing relevant information (the so called Kolmogorov–Chaitin definition). Another famous law in cybernetics (the *Law of Requisite Variety)* says that in order to be able to regulate a system one must have enough information about all the aspects that provide to it its degrees of freedom. For this reason, one has to wisely chose a representation capable of identifying as many as relevant aspects to be monitored and controlled as possible. Because of its basic philosophy MuSIASEM analysis tends to require a lot of different types of information that has to be gathered at different levels of analysis and from non-equivalent descriptive domains. As discussed more in detail in the next deliverable (Deliverable 4.2) where the use of the "end use matrix" will be illustrated, this requirement of a variety of data inputs implies facing various epistemological problems. A multiscale approach requires handling impredicative relations over data – i.e. the value of the sum depends on the values of the addends and viceversa, in the case in which the various values are taken simultaneously by different data sources (top-down statistical data versus bottom-up technical coefficients. On the other hand, the existence of a certain level of redundancy in the information space (what is called in the jargon of MuSIASEM the "Sudoku effect") provides more robustness to the representation and makes it possible to check the quality of the data set. The sudoku effect is particularly important because of the presence of many inconsistencies when trying to handle datasets coming from different sources through a multi-scale analysis. Moreover, in the definition of primary data, there is always a certain level of bias determined by the logic used by the statistical offices that not necessarily coincide with the logic that would be required to frame the performance of an economy in ecological terms or in social terms.

Moreover, it should be considered that the method proposed here is still in an experimental phase. As a matter of fact, Deliverable 4.2 represents the first attempt to validate the approach in relation to the task to characterize the energy performance of an economy and its economic sectors across different hierarchical levels and scales.

Discussion of the advantages of the proposed approach on the business as usual

The adoption of the rationale of an integrated analysis of the metabolic pattern across different scales makes it possible to identify which energy carriers are used by which societal compartments in order to express which expected functions.

When coming to the problem of how to identify targets for improving the energy performance of an economy this type of analysis provides an enormous advantage compared with the methods used right now:

1. an effective characterization of the metabolic pattern in relation to five aspects:

(i) what type of energy is used (definition of the typology of energy carrier or primary energy source);

(ii) how much is used (quantity per year);

(iii) how is it used (benchmark in terms of quantity per unit of output or quantity per unit of labor,

(iv) which sector (or technical process) is using it; and

(v) why is used (what is the expected task to be expressed, making it possible to assess the usefulness of the consumption).

2. An effective set of analytical tools that can be used not only as factors making it possible to characterize typologies of metabolic patterns, but also as indicators making possible a multi-criteria analysis:

(i) the degree of openness of the various elements considered (are the metabolic characteristics of the elements determined by technical coefficients?, or rather by the fact that what is produced is obtained by importing semi-finished components? Or even worse that there are products no longer produced that are directly imported by the economy?). This implies that the analysis of energy performance should always consider the aspect of performance determined by the domestic set of transformations and the "virtual transformations" that took place in order to make available the imported inputs;

(ii) the characterization based on processors determining the profile of inputs required for expressing a given economic activity (different types of energy carriers, power capacity, labor, water) and the profile of the resulting outputs (different types of emissions and wastes). Processors can be scaled across different levels making it possible to assess the consequences that changes in the characteristics of a processor at one scale may have on the characteristics of the processors at a different scale;

(iii) the association of the quantitative assessment of *flows* to the quantitative assessment of *funds* (power capacity) requires also that the analysis specify another important aspect of the energy conversions: the utilization factor of the power capacity. For example, the low utilization factor of "peaker" power plants (e.g. gas turbine producing peak electricity) has nothing to do with their lower efficiency, but rather to the fact that "peak" electricity has a different usefulness (function) than "base-load" electricity. This distinction between different "types" of electricity (peak, base-load, intermittent) cannot be detected without considering: 1. Flows (quantities of electricity); 2. Funds (size of power plants); and 3. utilization factor of the fund (the hours per year of utilization of the plant).

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